USEFUL INFORMATION

FOR

ENGINEERS;

BEING

A SERIES OF LECTURES

DELIVERED TO

THE WORKING ENGINEERS OF YORKSHIRE AND LANCASHIRE;

TOGETHER WITH

A SERIES OF APPENDICES,

CONTAINING

THE RESULTS OF EXPERIMENTAL INQUIRIES INTO THE STRENGTH OF MATERIALS, THE CAUSES OF BOILER EXPLOSIONS, ETC.

BY

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TO

THE RIGHT REVEREND

JAMES PRINCE LEE, D.D.,

LORD BISHOP OF MANCHESTER;

THAN WHOM THERE IS NO MORE SINCERE FRIEND

AND ADVOCATE OF EDUCATION

IN ITS MOST COMPREHENSIVE AND ENLIGHTENED SENSE,

THIS VOLUME IS INSCRIBED,

AS A MARK OF PERSONAL REGARD,

AND

IN ACKNOWLEDGEMENT OF THE EMINENT SERVICES

HE HAS RENDERED TO

THE EDUCATIONAL INSTITUTIONS OF HIS COUNTRY.

PREFACE.

In presuming to offer useful information to the members of an important profession, I would especially guard myself against an undue assumption of personal merit, and rather rest the justification of the title given to the present Volume upon the well-grounded public opinion, that the elementary principles of science are too much neglected in the study and practice of engineering.

It is generally admitted that one of the most popular and useful forms of imparting knowledge to others is that of public and entertaining Lectures, and I may therefore state that the Lectures which I have now the opportunity of publishing, were mostly prepared at the request of the Directors of the various educational institutions of the North of England, and delivered to the mixed assemblies of their Members. The circumstances of passing events gave to some of the addresses considerable local and temporary interest; but it does not by any means follow that, thus hastily conceived, the subjects of

which they treated were wanting in permanent value and importance to the mechanical student. On the contrary, the preparation of what I had to say, constantly opened out new fields of inquiry, and laid bare more openly the deficiencies in the education—and therefore in the existing intelligence—of a numerous and important class of society. My object was to impart to working engineers, in intelligible and simple terms, all I myself knew of the varied branches of practical science which their calling embraces, and hence my main reliance was on the results of my own practice and experience. But beyond this I had necessarily much to study in the labours of others, and my acknowledgements are therefore due to those authors whose writings have been quoted in confirmation of my own views. To the writings of Robinson, Arago, Dalton, and Pambour I am especially indebted for certain confirmatory remarks and experiments on the nature and properties of steam and other elastic fluids. There is much yet to learn in this department of scientific research. Mr. Joule's new theory of heat, and the experimental inquiries of Regnault on saturated steam, are likely to produce important changes and greatly extended improvements in the theory and construction of the steam-engine, as well as in the mechanical application of other elastic fluids. Deeply impressed with the importance of the subject and the great difficulties surrounding it, I was induced to undertake the task from the consideration, that although I am not perhaps the most competent person to elucidate many of the subjects treated of in these Lectures, yet, in the absence of higher authorities, I felt I might render some service

to the practical man, by placing within his reach some of the most remarkable laws of heat connected with the theory and application of steam as a mechanical agent. In thus acknowledging my own deficiencies, I shall consider my labour to be fully remunerated if I succeed in engaging the attention of those who are deprived, by their avocations and the limited time at their disposal, of the ordinary means of instruction.

In confirmation of many of the opinions advanced in the Lectures, I have deemed it necessary to give the experiments on the strength of sheet-iron plates and their riveted joints in full; as well as the direct experiments on the strengths of boilers, on the pressure of steam at different temperatures, and on the causes of boiler explosions.

To constructive science I have given special attention, and I venture to hope that the experiments and recommendations relating to the best form and construction of boilers and other vessels subjected to severe strain will be carefully considered by practical boiler-makers and engineers, and thus lead to greater security of life and property.

In treating of the economy of fuel and the prevention of smoke, I have endeavoured to show that economy in the consumption of coal fuel is attainable *without smoke*; and I have converted the paper read before the British Association for the Advancement of Science into the form of Lectures, in order to render the subject easier of acquirement to those who are desirous of abating a serious nuisance, and of establishing a better and more economical system of combustion.

It would appear almost superfluous to insist upon the value

of a sound knowledge of practical science; yet how few possess it, and how many will refuse to admit that it is essential to the successful practice of the mechanical and industrial arts! It cannot therefore be too frequently or too firmly asserted, that in order to advance the science of engineering, we must combine a knowledge of the first principles of the exact sciences with skill in construction;—that a perception of and acquaintance with the unerring laws which science reveals, is the only sound basis for creditable results;—and with the view of encouraging the practical man in the pursuit of this knowledge, I have cited examples where industry and perseverance in the development and prosecution of more than one department of science and art have led not only to worldly success, but to honour and renown.

Metallic constructions open a wide field for investigation, and volumes might be written on this subject before it could be exhausted. On the present occasion, however, my observations have been confined to iron ship-building, from the circumstance that I was among the first to take up this important branch of national industry, and embark in the construction of iron vessels upon a large scale. Nearly twenty years ago I made a series of experiments on malleable iron plates and rivets, the results of which were subsequently published in the Transactions of the Royal Society, and are now republished in the Appendix to the Lectures. These experiments, as well as those undertaken to determine the form and strength of the Britannia Tubular Bridge, apply with considerable certainty to almost every form of metallic construction, and have already

been, I trust, of great value in boiler making and ship and bridge building. In giving my views on this subject, I have not attempted to offer an opinion on those forms of ships which come within the province of the naval designer, but have simply endeavoured to show in what position the material should be placed so as to attain the maximum of strength, in the general mass in its riveted form, as it appears in the iron ship.

In my attempts in the succeeding Lectures to investigate the nature and properties of steam, practically considered, I had to bring not only the whole of my experience and knowledge to the task, but I had to consult the writings of some of the most distinguished men of science since the days of Dr. Black, when he first announced his theory of latent heat.

It was not without great diffidence that I approached this question, inasmuch as the labours of such men as Black, Robinson, Watt, Southern, &c. in former days, and those of Arago, Dulong, Pambour and Regnault of more recent date, made me sensibly alive to the difficulties which, in the present state of our knowledge, surround such an inquiry. I have referred, in the course of my investigations, to all these authorities; and although much has been accomplished in elucidation of the subject by these writers, there is, nevertheless, a wide field yet to be explored before our knowledge of steam, and its application as a moving power, can be said to be clearly and explicitly understood.

Viewing the subject in this light, I have not hesitated to direct the attention of the practical engineer to the new dis-

coveries relative to the laws of elastic fluids, contained in the researches of my friend Mr. Joule, Professor Thomson and Regnault. To the investigations of those writers I am indebted for new and useful information.

On the employment and use of high-pressure steam, I have dwelt with more than ordinary attention: I have done so from a conviction that we have yet much to learn in relation to its application, retention and improved expansion.

Unquestionably, considerable advances have been made within the last ten years in the construction of the steam-engine; but we are still far from having attained a perfect construction either in the land, the marine, or the locomotive engine. It is true, that in our manufactories we are now performing almost double the work with the same quantity of fuel that was formerly performed; and nearly the same improvements and economy have been accomplished by the use of high steam on board our steamers; but we have still much further to go, for by a careful and judicious application of high steam—in improved engines,—probably working from 150 to 200 lbs. on the square inch, we may venture to look forward to a new and important era in the history of steam and the steam-engine*.

I cannot conclude this Preface, already too long, without some words of acknowledgement to my friend Mr. Tate, for his

* The present war has led to the employment of high-pressure steam vessels in the Navy, and I am glad to find that the steam department of the Royal Navy is now alive to the importance of using high steam in vessels of war. *Vide* a circular note just issued by the Admiralty at the end of the Appendix.

able mathematical investigations, a labour which has been cheerfully rendered on his part, and the value of which can only be appreciated by those who, like myself, have found his researches so highly advantageous. If I have reserved his name to the last of those to whom I am indebted, it is certainly not because I value his services the least.

In conclusion, I have to express my acknowledgements to the various Institutions with which I am connected, for the readiness with which they permitted me to avail myself of my contributions to their Transactions for republication; and I sincerely hope that the Volume now offered may be useful, not only to the Members of those Institutions, but to the wider circle of working engineers for whom it has been exclusively written.

W. F.

Manchester, Dec. 10th, 1855.

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APPENDIX VI*.

ON STEAM-ENGINE BOILERS.

ERRATA.

Page 155, line 24, *for* λ, in formula $\lambda + T = 1146{\cdot}6$, *read* $\lambda' =$ the units of latent caloric.

Page 175, line 21, *for* Mr. Smith, Huddersfield *read* Mr. Green, Wakefield.

since its introduction by Watt, three-quarters of a century ago, have been very numerous and varied; and although the progression in its applications and improvements has been most rapid and wonderful, we are still undecided as to the best form of its construction. Sound principles scientifically applied, and the gradually increasing excellence of our mechanical workshop, have enabled us to attain the great perfection which characterises the working parts of the modern steam-engine. Since the steam-engine itself may be regarded as a comparatively perfect machine, I shall confine my observations almost exclusively to that very important and necessary adjunct—*the Boiler*—which is the source of its power. Even this limitation of the subject presents to us a very wide field of inquiry. In the earliest steps of the investigation we become perplexed with the endless variety of forms and constructions which at different

periods have been adopted by engineers, and which have never, unfortunately, received the same judicious attention that has been paid to the other parts of the steam-engine. This is an anomalous and much to be regretted fact, for the boiler, being the source of the motive power, is undoubtedly one of the most important parts of the whole machine. Upon its proper proportions and arrangements for the generation of steam depend the economy and regularity with which the engine can be worked, and upon the strength and excellence of its workmanship depends the safety of the lives and property of those who come in contact with it. Regarding, as we do, the steam-engine as one of the most active agents in the extension of our prosperity and in the civilization of the world, and seeing how it is mixed up with the daily duties and workings of society, the safety and efficiency of every part of this great machine, and more especially of the *boiler*, must necessarily be considered as a subject of national importance; and I feel gratified by being called upon to lay before you such knowledge and experience on this subject of deep interest as I myself possess.

I propose to consider the Boiler in its *Construction*, *Management*, *Security*, and *Economy*.

1st. As to the *Construction*.—Here I shall have to go a little into detail, in order to show the absolute necessity that exists for adhering to certain rules of form and other points of construction, essential in the practice of mechanical engineers, in order to attain the maximum of strength with the minimum of material. In boilers this is the more important, as any increase in the thickness of the plates obstructs the transmission of heat, and exposes the rivets as well as the plates to injury on the side exposed to the action of the furnace.

It has generally been supposed that the rolling of boiler plate iron gives to the sheets greater tenacity in the direction of their length than in that of their breadth; this is, however, not correct; as a series of experiments which I made some years since fully proves that there is no difference in the tensile strength of boiler plates whether torn asunder in the direction of the fibre, or

across it. From five different sorts of iron the following results were obtained:—

Description of Iron.	Mean breaking weight in tons in the direction of the fibre.	Mean breaking weight in tons across the fibre.
Yorkshire plates	25·77	27·49
Yorkshire plates	22·76	26·37
Derbyshire plates	21·68	18·65
Shropshire plates	22·82	22·00
Staffordshire plates	19·56	21·01
Mean	22·51	23·10*

From this it appears that we may safely use iron plates in the construction of boilers in whatever direction may best suit the convenience of the maker. It has been supposed that wrought iron plates, when exposed to intense heat—such as we observe in those of a boiler over the furnace—lose a considerable portion of their strength. On this question we are not, however, well informed, as it will be seen, on referring to Appendix No. I., that the results of the experiments given above were made at the ordinary temperature of the atmosphere; and as boilers in their working state are considerably above that temperature, it may be interesting to know what effect greatly increased temperature has upon the tenacity of wrought iron. In cast iron I have already determined by experiment the effects of temperature on its powers of resistance to a transverse strain; but it was reserved for the Committee of the Franklin Institute to conduct similar experiments on malleable iron; and as these experiments appear to be conclusive, and approximate closely to my own up to 600°, where the strength is not seriously, if at all impaired, I have the less hesitation in presenting the results of the Committee in the form given in the Report.

After describing the series of experiments numerically as they were made, the Report goes on to say, "On a survey of the preceding discussions, it will be seen that in determining the maximum at each point of fracture, it has been necessary to resort sometimes to experimental, and sometimes to calculated results, but in several cases the two operate as checks upon each other.

* In Appendix No. I. will be found a detailed account of the experiments, extracted from a paper read before the Royal Society, 1850.

On attempting to extend the principle to trials made below the temperatures already cited, we are liable to encounter an ambiguity in the results, owing to the fact that the maximum tenacity is not generally to be obtained without having carried the previous temperatures to about 550° or 600°, and the tension to nearly or quite that of the original strength of the metal when cold."

These facts are confirmed in my experiments to determine the effects of temperature on cast iron. In the more fluid, or finer descriptions of iron, I found a loss of 10 per cent. from 21° to 190°, but in the harder and stronger descriptions of iron, No. 3, there was nearly the same increase of strength up to 600°; and from these confirmatory results, we may infer that the infusion of heat into metallic substances, such as cast and wrought iron, does not produce any serious diminution of their strength up to a temperature of 600°. On the contrary, the following Table indicates nearly the same results from 520° up to 662°,

Table of Temperatures and Ratios of Strengths.

No. of the comparison.	Marks of the bar.	Temperature observed.	Tenacity observed.	Maximum tenacity at the point of fracture.	Manner in which the maximum was obtained.	Diminution by heat in parts of the maximum tenacity.	Irregularity of the metal in parts of the original strength.
1	224 B	520	58,451	63,275	Experiment	·0738	·0992
2	Salisb. iron.	570	60,398	60,398	Ditto	·0869	·1125
3	90	596	57,682	57,682	Calculation	·0899	·2401
4	90	600	56,938	63,086	Ditto	·0964	·2401
5	219 A	630	60,010	67,033	Experiment	·1047	·1440
6	150	662	58,182	65,785	Ditto	·1155	·0644
7	152	722	54,442	64,483	Calculation	·1436	·0507
8	14	732	53,378	62,736	Experiment	·1491	·1310
9	150	734	57,903	68,407	Calculation	·1535	·0644
10	16	766	54,819	65,176	Experiment	·1589	·1563
11	149	770	54,781	65,445	Calculation	·1627	·0234
12	214	824	55,892	70,080	Ditto	·2010	·0413
13	214	932	45,531	68,202	Ditto	·3324	·0413
14	232	947	42,401	66,193	Experiment	·3593	·0446
15	{214 152}	1030	37,587	68,071	Calculation	·4478	·0460
16	227	1111	27,603	61,531	Ditto	·5514	·0330
17	227	1155	21,967	54,992	Ditto	·6000	·0330
18	229	1159	25,620	64,234	Ditto	·6011	·1102
19	227	1187	21,913	60,102	Ditto	·6352	·0330
20	226	1237	21,298	63,065	Ditto	·6622	·1147
21	226	1245	20,703	63,065	Ditto	·6715	·1147
22	226	1317	18,913	63,065	Ditto	·7001	·1147

where it will be observed there is no material change in its power of resistance. This Table exhibits also, according to the Report of the Committee, "the observed temperatures and corresponding tenacity of metal with the calculated or experimental maximum of strength,—the ratio of the observed diminution to the maximum tenacity, and the irregularity of the metal in parts of the original strength at ordinary temperatures.

"From the eighth column of the preceding Table, it appears that of these fifteen different specimens of iron, the mean irregularity of structure is 10 per cent. of the mean strength when tried cold.

"For the purpose of ascertaining, approximately, the law of decrease in strength by temperature, an investigation was made similar to that adopted for copper, embracing, however, only twelve of the points contained in the preceding Table.

"As some of the experiments which furnished the standards of comparison for strengths at ordinary temperatures, were made at 80°, and as at that point small variations in respect to heat appear to affect but very slightly the tenacity of iron, it is conceived that for practical purposes at least, the calculations might be commenced from that period.

"Eighty degrees are therefore deducted from each temperature in the foregoing Table, and the remainders used, instead of the numbers commencing from the 0 of our scale. It will be found, that, with the exception of a slight anomaly between 520° and 570°, amounting to —·18, the numbers expressing the ratio between the elevations of temperature, and the diminutions of tenacity, constantly increase until we reach 932°, at which it is 2·97, and that from this point the ratio of diminution decreases to the limits of our range of trials ·1317, where it is 2·14. It will also be observed, that the diminution of tenacity at 932°, where the law changes from an increasing to a decreasing rate of diminution, is almost precisely one-third of the total or maximum of strength of the iron at ordinary temperatures."

Next to the tenacity of the plates, comes the question of rivet-

ing, or the best and surest means of securing them together. On this part of the subject we have been widely astray, and it required some skill, and no inconsiderable attention, in conducting the experiments, to convince the unreflecting portion of the public, and even some of our boiler-makers, that the riveted joints were not stronger than the plate itself. At first sight this would appear to be the case, but a moment's reflection will soon convince us of the contrary: in punching holes along the edge of a plate it is obvious that the plate must be weakened to the extent of the sectional areas punched out, and that it is [redacted] impossible, under the circumstances, to retain the same strength in the material after such diminution has been effected, as existed in the previously solid plate. This was clearly demonstrated by a series of experiments which were made some years since*, and in which the strength of almost every description of riveted joints was determined by tearing them directly asunder. The results obtained from these experiments were conclusive as regards the relative strength of riveted joints and the solid plates. In two different kinds of joints—double and single riveted—the strengths were found to be, in the ratio of the plate, as the numbers 100, 70, and 56.

Assuming the strength of the plate to be	100
The strength of a double riveted joint would be, after allowing for the adhesion of the surfaces of the plate.............	70
And the strength of a single riveted joint..................	56

These proportions of the relative strengths of plates and joints may therefore, in practice, be safely taken as the standard value, in the construction of vessels required to be steam- and water-tight, and subjected to pressure varying from 10 lbs. to 100 lbs. on the square inch.

In the construction of boilers exposed to severe internal pressure, it is desirable to establish such forms, and so to dispose the material, that the greatest strength may be supplied in the direction of the greatest strain; and in order to accomplish this, it will be necessary to consider whether the same arrangement

* Vide Appendix No. I. p. iv.

be required for all diameters, or whether the form as well as the disposition of the plates should not be changed. To determine these questions in cylindrical boilers, recourse must be had to experiment, or such deduction as may apply to any given case, and such as is founded upon unerring data derived from experimental research. On this head I am fortunate in having before me the calculations of Professor W. R. Johnson, of the Franklin Institute of America, whose inquiries into the strength of cylindrical boilers are of great value, and of which the following is a short and useful abstract:—

"1st. To know the force which tends to burst a cylindrical vessel in the longitudinal direction, or, in other words, to separate the *head* from the curved *sides*, we have only to consider the actual area of the head, and to multiply the units of *surface* by the number of units of *force* applied to each superficial unit. This will give the total *divellent* force in that direction.

"To counteract this, we have, or may be conceived to have, the tenacity of as many longitudinal bars as there are lineal units in the circumference of the cylinder. The united strength of these bars constitutes the total retaining or *quiescent* force, and at the moment when rupture is about to take place, the *divellent* and the quiescent forces must obviously be equal.

"2nd. To ascertain the amount of force which tends to rupture the cylinder along the curved side, or rather along the opposite sides, we may regard the pressure as applied through the whole breadth of the cylinder upon each lineal unit of the diameter. Hence the total amount of force which would tend to divide the cylinder in halves, by separating it along two lines, on opposite sides, would be represented by multiplying the diameter by the force exerted on each unit of surface, and this product by the length of the cylinder. But even without regarding the length, we may consider the force requisite to rupture a *single band* in the direction now supposed, and of one lineal unit in breadth; since it obviously makes no difference whether the cylinder be long or short, in respect to the ease or

difficulty of separating the sides. The *divellent* force in this direction is therefore truly represented by the diameter multiplied by the pressure per *unit of surface*. The retaining or *quiescent* force, in the same direction, is only the strength or tenacity of the two opposite sides of the supposed band. Here also at the moment when a rupture is about to occur, the divellent force must exactly equal the quiescent force."

In the subsequent portion of the paper, Mr. Johnson appears to reason on the supposition that there are no joints in the plates, and that the tenacity of the iron is equal to 60,000 lbs. —rather more than 26 tons to the square inch. Now we have shown by the results of the experiments already adduced, that ordinary boiler plates will not bear more than 23 tons to the square inch, and as nearly one-third of the material is punched out for the reception of the rivets, we must still further reduce the strength, and take 15 tons, or about 34,000 lbs.* on the square inch, as the tenacity of the material, or the pressure at which a boiler would burst.

This I should consider in practice as the maximum power of resistance of boiler plates in their riveted state, and I will now trouble you to follow me in a very concise and I trust not uninteresting investigation, as to the bearing powers of boilers, and the pressure at which they can be worked with safety.

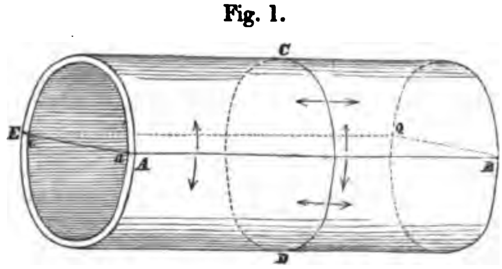
It follows from the general principles which have been stated, that the divellent force tending to rupture the boiler plates in longitudinal lines parallel to the axis of the boiler is in the direct ratio of the diameter of the boiler; whereas the divellent force tending to rupture the plates in transverse lines, formed by section taken perpendicular to the axis of the boiler, is in the ratio of the squares of the diameters. THE THICKNESS OF THE PLATES OF CYLINDRICAL BOILERS SHOULD BE IN PROPORTION TO THEIR DIAMETERS; for as the force tending to burst a boiler of a

* By experiment it is found that the strength of the riveted joints of boilers is only about one-half the strength of the plate itself; but taking into consideration the crossing of the joints, 34,000 lbs. may reasonably be taken as the tenacity of the riveted plates, or the bursting pressure of a cylindrical boiler.

given length and subject to a given pressure varies simply as the diameter of the boiler, and as the resistance of the plates varies as their thickness, it follows that the thickness of the plates, in order to resist a given pressure of steam per square inch, must be in proportion to the diameter of the boiler. It will be afterwards shown that the weakest portions of the plates are in the longitudinal lines drawn parallel to the axis of the boiler*. For example, let us take two boilers, one 3 feet in diameter and the other 6 feet, and suppose each to be subject to a pressure of 40 lbs. on the square inch. In this condition, it is evident that the area or number of square inches in the end of a 3-feet boiler is to that of the area of the 6-feet boiler

* Let A B C D represent a cylindrical boiler; A B Q E a longitudinal section passing through the axis of the boiler; and D C a transverse section perpendicular to the axis; put l=A B the length of the boiler, $2r$ or $d=ae$ the internal diameter, c=Aa=Ee the thickness of the boiler plates, T= the tenacity in lbs. of a square inch of the material, and P= the pressure of the steam in lbs. for every square inch; then the pressure of the steam tending to produce a longitudinal rupture in the section A B Q E, will act upwards and downwards upon the internal section, having its area equal to $d \times l$;

Fig. 1.



$\therefore$ Pressure of the steam to produce longitudinal rupture = area internal section $\times$ P=dlP. .... (1)

This result shows that the divellent force tending to produce longitudinal rupture, that is, to separate the plates along the lines A B and E Q, is in the direct ratio of the diameter of the boiler.

Again, we have—

Resistance of the section A B Q E to rupture = area section $\times$T=$2lc$T. (2)

Now when rupture is about to take place, formula (1) becomes equal to (2);

$$\therefore\ dlP=2lcT,$$

$$\therefore\ c=\frac{dP}{2T}, \qquad (3)$$

which gives the thickness of the boiler plates when rupture is upon the point of taking place, under the pressure, P, of the steam. Hence it appears that

60,000
50
3,000,000

as 1 to 4; and by a common process of arithmetic it will be found that the edges of the plates forming the cylindrical part of the 3-feet boiler are subject (at 40 lbs. on the square inch) to a pressure of 40,712 lbs.—upwards of 18 tons; whereas the plates of the 6-feet boiler have to sustain a pressure of 162,848 lbs., or 72 tons, which is quadruple the force to which the boiler only one-half the diameter is exposed; and the circumferences being only as 2 to 1, there is necessarily double the strain upon the cylindrical plates of the large boiler.

the thickness of the plates of cylindrical boilers should be in proportion to their diameters.

The section, A B Q E, passing through the axis of the cylinder is obviously the weakest longitudinal section.

We shall now consider the conditions of rupture through the transverse section C D.

Pressure of steam tending to produce rupture in the section C D = area internal section $\times P = \frac{\pi d^2 P}{4}$ .... (4)

This result shows that the divellent force tending to produce transverse rupture varies as the square of the internal diameter of the boiler.

Area of the material in the section D C$=\pi c(c+d)$;

∴ Resistance section D C to rupture $=\pi c(c+d)$T................ (5)

But when rupture is about to take place, formula (4) must be equal to formula (5);

$$\therefore\ \pi c(c+d)T = \frac{\pi d^2 P}{4};$$

$$\therefore\ c\left(\frac{c}{d}+1\right)T = \frac{dP}{4};$$

neglecting $\frac{c}{d}$ as being very small, we get

$$c = \frac{dP}{4T} \quad \text{..........................} \quad (6)$$

Comparing this expression with (3), we find that the transverse section has double the strength of the longitudinal section. From this proposition it follows that a boiler constructed with plates of uniform thickness is most liable to undergo rupture in its longitudinal sections.

Example. Required the thickness of the plates of a boiler 20 feet long and 5 feet in diameter in order to stand the pressure of steam at 204 lbs. per square inch, the tenacity of the metal being 34,000 lbs. per square inch.

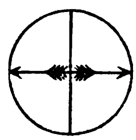
Here by formula (3) we have,—

$$d=5\times 12=60,\ P=204,\ \text{and}\ T=34{,}000,$$

$$\therefore\ c=\frac{60\times 204}{2\times 34000}=\cdot 18\ \text{inch}.$$

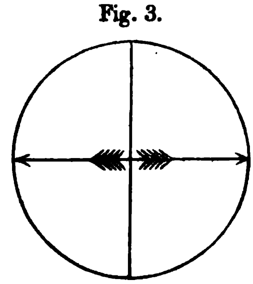
Let us, for the sake of illustration, suppose the two cylindrical boilers, such as we have described, to be divided into a series of hoops of 1 inch in width; and, taking one of these hoops in the 3-feet boiler, we shall find it exposed, at a pressure of 40 lbs. on the square inch, to a force of 1440 lbs., acting on each side of a line drawn through the axis of a cylinder 36 inches diameter and 1 inch in width, and which line forms the diameter of the circle. Now this force causes a strain upon each of the points *a a* in the direction of the arrows in the annexed diagram of the 3-feet circle of 720 lbs.,

Fig. 2.



and assuming the pressure to be increased till the force becomes equal to the tenacity or retaining powers of the iron at *a a*, it is evident, in this state of the equilibrium of the two forces, that the least preponderance on the side of the internal pressure would produce fracture. And, suppose we take the plates of which the boiler is composed at one quarter of an inch thick, and the ultimate strength at 34,000 lbs. on the square inch, we shall have $\frac{34,000}{36 \times 2} = 472$ lbs. per square inch, as the bursting pressure of the boiler. Again, as the forces in this direction are not as the squares, but simply as the diameters, it is clear that at 40 lbs. on the square inch, we have in a hoop an inch in depth, or that portion of a cylinder whose diameter is 6 feet, exactly double the force applied to the points *b b*, which was acting on the points *a a*, in the diameter of 3 feet. Now, assuming the plates to be a quarter of an inch thick, as in the 3-feet boiler, it follows, if the forces at the same pressure be doubled in the large cylinder, that the thickness of the plates must also be doubled in order to sustain the same pressure with equal security; or what is the same thing, the 6-feet boiler must be worked at half the pressure, in order to ensure the same degree of safety as that attained in the 3-feet boiler at double the pressure. From

Fig. 3.



these facts we may conclude, that boilers having increased dimensions should also have increased strength in the ratio of their diameters; or, in other words, the plates of a 6-feet boiler should be double the thickness of the plates of a 3-feet boiler, and so on in proportion as the diameter is increased.

The relative power of force applied to cylinders of different diameters becomes more strikingly apparent when we reduce them to their equivalents of strain per square inch, as applied to the ends and circumference of the boiler respectively. In the 3-feet boiler, working at 40 lbs. pressure, we have a force equal to 720 lbs. upon an inch width of plate, and one quarter of an inch thick, or 720 by 4=2880 lbs., the force per square inch upon every point of the circumference of the boiler.

Let us now compare this with the actual strength of the riveted plates themselves, which taken as before at 34,000 lbs. on the square inch, we arrive at the ratio of pressure as applied to the strength of the circumference as 2880 to 34,000, nearly as 1 to 12, or 472 lbs. per square inch, as the ultimate strength of the riveted plates.

These deductions appear to be true in every case as regards the resisting powers of cylindrical boilers, to a force radiating in every direction from the axis towards the circumference; but the same law is, however, not maintained when applied to the ends, or, to speak technically, to the angle-iron and riveting where the ends are attached to the circumference. Now, to prove this, let us take the 3-feet boiler, where we have about 113 inches in the circumference, and upon this circular line of connexion we have, at 40 lbs. to the square inch, to sustain a pressure of 18 tons, which is equal to a strain of 360 lbs. acting longitudinally upon every inch of the circumference. Apply the same force to a 6-feet boiler, with a circumference or line of connexion equal to 226 inches, and we shall find it exposed to exactly four times the force, or 72 tons; but in this case it must be borne in mind that the circumference is doubled, and consequently the strain, instead of being in the quadruple ratio, is only doubled, or a force equal to 720 lbs. acting

longitudinally as before upon every inch of the circumference of the boiler.

Again, if we refer to the comparative merits of the plates composing cylindrical vessels subjected to internal pressure, they will be found in this anomalous condition, that the strength in their longitudinal direction is twice that of the plates in the curvilinear direction. This appears by a comparison of the two forces, wherein we have shown that the ends of the 3-feet boiler, at 40 lbs. internal pressure, sustain 360 lbs. of longitudinal strain upon each inch of a plate a quarter of an inch thick; whereas plates of the same thickness have to bear in the curvilinear direction a strain of 720 lbs. This difference of strain is a difficulty not easily overcome, and all that we can accomplish in this case will be to exercise a sound judgement in crossing the joints, in the quality of the workmanship, and the distribution of the material. For the attainment of these objects, the following Table, which exhibits the proportionate strength of cylindrical boilers from 3 to 8 feet in diameter, may be useful*.

TABLE of equal strengths in Cylindrical Boilers from 3 to 8 feet diameter, showing the thickness of metal in each respectively, at a pressure of 450 lbs. to the square inch.

Diameter of Boilers. ft.	in.	Bursting pressure—equivalent to the ultimate strength of the riveted joint—as deduced from experiment, 34,000 lbs. to the square inch.	Thickness of the plates in decimal parts of an inch.
3	0	450 lbs.	·250
3	6		·291
4	0		·333
4	6		·376
5	0		·416
5	6		·458
6	0		·500
6	6		·541
7	0		·583
7	6		·625
8	0		·666

Boilers of the simple form, and without internal flues, are subjected only to one species of strain; but those constructed

* In this discussion we have not taken into account the effect that boilers

with internal flues are exposed to the same tensile force which pervades the simple form; and further, to the force of compression which tends to collapse, or crush the material of the internal flues. In the cylindrical boiler with round flues, the forces are diverging from the central axis as regards the outer shell, and converging as applied to every separate flue which the boiler contains.

These two forces in a steam-boiler are in constant operation; the tendency of the one being to tear up the external plates and force out the ends, and the other to destroy the form and to force the material into the central area of the flues. These two forces operate in a widely different manner upon the resisting powers of the boiler, which, taken in the direction of its exterior envelope, has to resist a tensile strain operating in every direction from within, and the internal flues, acting as an arch, offer a powerful resistance to compression from without. It might be instructive as well as interesting to exhibit the nature of these powers, and determine the law by which vessels of this description are retained in shape; but this can only be done by experiment, and as these experiments would have to be conducted upon a large scale, and with great accuracy, in order to arrive at satisfactory results, we must abandon the idea for the present, and content ourselves with such information as we already possess. At some future period I may possibly devote my attention to this subject; it is one of great importance, and a series of well-conducted experiments would, I make no doubt, supply valuable data in the varied requirements of boiler construction, and their

constructed with central flues will have upon the flat ends in diminishing the strain upon the anterior or the exterior circumference where the ends are united to the cylinder. On the contrary, I have purposely omitted that element of strength in the calculation, and for the sake of illustration I have assumed that the boiler has no internal flues, and that the circumference is subjected to the whole strain in the ratio—as before noticed—of the squares of the diameters. In cases where boilers are constructed with internal flues, there will be this advantage as regards strength; namely, that the outer shell will be relieved from a longitudinal strain to the extent of their respective areas or circumferences.

comparative powers of resistance to the united force of tension and compression.

From the existing state of our knowledge, we must rest satisfied with the fact, that the resisting powers of cylindrical flues to compression will be inversely as their diameters; and we may therefore conclude that a circular flue, 18 inches in diameter, will resist double the pressure of one 3 feet in diameter. Hence it follows that the resistance of wrought-iron plates of the circular form is to the force of compression inversely as their diameters—the same, but with greatly diminished powers, as compared with the resistance of wrought-iron cylindrical plates to tension.

To show the amount of strain upon a high-pressure boiler 30 feet long, 6 feet diameter, having two centre flues, each 2 feet 3 inches diameter, working at a pressure of 50 lbs. on the square inch or 7200 lbs. per sq. ft., we have only to multiply the number of square feet of surface, 1030, exposed to pressure, by 7200, and we have the force of 3319 tons, which a boiler of these dimensions has to sustain. I mention this to show that the statistics of pressure, when worked out, are not only curious in themselves, but instructive as regards a knowledge of the retaining powers of vessels so extensively used, and on which the bread of thousands depends. To pursue the subject a little further, let us suppose the pressure to be at 450 lbs. on the square inch, which a well-constructed boiler of this description will bear before it bursts, and we have the enormous force of 29,871, or nearly 30,000 tons bottled up within a cylinder 30 feet long and 6 feet diameter.

This is, however, inconsiderable when compared with the locomotive, and some marine boilers, which, from the number of tubes, present a much larger extent of surface to pressure. Locomotive engines are usually worked at 80 to 100 lbs. on the inch; and, taking one of the usual construction, we shall find at 100 lbs. on the inch that it rushes forward on the rail with a pent-up force, within its interior, of nearly 60,000 tons, and this force is rather increased than diminished at an accelerated speed.

In a stationary boiler charged with steam at a given pressure, it is evident that the forces are counteracted by the resistance of the plates, and the strain being the same in all directions, there will be no tendency to motion. Supposing, however, this equilibrium to be destroyed by accumulative pressure till rupture ensues, it then follows that the resisting forces in one direction having ceased, the others in an opposite direction being active, would project the boiler from its seat with a force equal to that which is discharged through the orifice of rupture. The direction of motion would depend upon the position of the ruptured part. If in the line of the centre of gravity, motion would ensue in that direction; if out of that line, an oblique or rotatory motion round the centre of gravity would be the result.

The quantity of motion produced in one direction would be equal to the quantity of motion in the opposite direction; and the velocity with which the body would move would be in the ratio of the impulsive force, or force of explosion through the rupture. These investigations are, however, more in the province of the mathematician, and may easily be computed from the well-known formulæ of accumulated work*.

We now come to the rectangular forms, or flat surfaces, which are not so well calculated to resist pressure. Of these we may

* Let $q=$ the number of cubic feet of steam in the boiler at the moment of explosion; P its pressure per square inch; P_1 the pressure of the external air; W the weight of the boiler in lbs., together with the material connected with it; V the velocity in feet per second produced in this mass by the recoil of the explosion; then, by Tate's 'Mechanical Philosophy applied to Industrial Mechanics,' pages 58 and 328, we have

The work accumulated in the mass by the recoil of the explosion $=\dfrac{W\times V^2}{2g}$.

The work due to the expansion of the steam $=144qP\log\dfrac{P}{P_1}$. Supposing the motion of the mass to take place in the direction of the line of discharge, we have

$$\frac{WV^2}{2g}=144qP\log\frac{P}{P_1},$$

$$\therefore\ V=\sqrt{\frac{288gqP}{W}\log\frac{P}{P}}.$$

instance the fire-box of the locomotive boiler, the sides and flues of marine boilers,—the latter of which, by the bye, are now superseded by those of the tubular form,—and the flat ends of the cylindrical boilers, and others of weaker construction.

The locomotive boiler is frequently worked up to a pressure of 120 lbs. on the square inch, and at times, when rising steep gradients, I have known the steam nearly as high as 200 lbs. on the inch. In a locomotive boiler subject to such an enormous working pressure, it requires the utmost care and attention on the part of the engineer to satisfy himself that the flat surfaces of the fire-box are capable of resisting that pressure, and that every part of the boiler is so nearly balanced in its powers of resistance, that when one part is at the point of rupture, every other part is on the point of yielding to the same uniform force. This appears to be an important consideration in mechanical constructions of every kind, as any material applied for the security of one part of a vessel subject to uniform pressure, whilst another part is left weak, is so much material thrown away; and in stationary boilers, or in moving bodies, such as locomotive engines and steam vessels, it is absolutely injurious, at least so far as the parts are disproportionate to each other, and the extra weight, when maintained in motion, becomes an expensive and unwieldy encumbrance. A knowledge of the strength of the materials used, and of sound judgement in its distribution, are therefore among the most essential qualifications of the practical engineer. Our limited knowledge, and defective principles of construction, are manifest from the numerous abortions which exist, and although I am free to communicate all that I know on the subject, I nevertheless find myself deficient in many of the requirements necessary for the attainment of sound principles of construction.

Reverting to the question more immediately under consideration, it is, however, essential to give the requisite security to those parts which, if left unsupported, would involve the public as well as ourselves in the greatest jeopardy.

The greater portion of the fire-boxes of locomotive boilers, as

before noticed, have the rectangular form, and in order to economise heat and give space for the furnace, it becomes necessary to have an interior and exterior shell. That which contains the furnace is generally made of copper, firmly united by rivets, and the exterior shell, which covers the fire-box, is made of iron and united by rivets, in the same way as the copper fire-box. Now these plates would of themselves be totally inadequate, unless supported by riveted stays, to sustain the pressure. In fact, with one-tenth the strain, the copper fire-box would be forced inwards upon the furnace, and the external shell bulged outwards, and with every change of force these two flat surfaces would move backwards and forwards, like the sides of an inflated bladder, at the point of rupture. To prevent this, and give the large flat surfaces a degree of strength equal to the other parts of the boiler, wrought iron or copper stays, $\frac{3}{4}$ to 1 inch thick, are introduced; they are first screwed into the iron and copper on both sides to prevent leakage, and then firmly riveted to the interior and exterior plates. These stays are from 4 to 6 inches asunder, forming a series of squares, and each of them will resist a strain of about fifteen tons before it breaks.

Let us now suppose the greatest pressure contained in the boiler to be 200 lbs. on the square inch, and we have $6 \times 6 \times 200 = 7200$ lbs. or $3\frac{1}{4}$ tons, the force applied to a square of 36 inches. Now as these squares are supported by four stays, each capable of sustaining fifteen tons, we have $4 \times 15 = 60$ tons as the resisting powers of the stays, but the pressure is not divided amongst all the four, but each stay has to sustain that pressure, consequently the ratio of strength to the pressure will be as $4\frac{1}{2}$ to 1 nearly, which is a very fair proportion for the resisting power of that part*.

We have treated of the sides, but the top of the fire-box and the ends have also to be protected, and there being no plate but the circular top of the boiler from which to attach stays, it

* For a further illustration of this subject see experiments on Locomotive Boilers, Appendix No. II.

has been found more convenient and equally advantageous to secure those parts by a series of strong wrought iron bars, from which the roof of the fire-box is suspended, and which effectually prevent it from being forced down upon the fire. It will not be necessary to go into the calculations of those parts; they are, when riveted to the dome or roof, of sufficient strength to resist a pressure of 300 to 400 lbs. on the square inch. This is, however, generally speaking, the weakest part of the boiler, with the exception, probably, of the flat end above the tubes in the smoke-box, if not carefully stayed.

In the flat ends of cylindrical boilers, and those of the marine principle, the same rule applies as regards construction, and a due proportion of the parts, as in those of the locomotive boilers, must be closely adhered to. Every description of boiler used in manufactories, or on board of steamers, should, in my opinion, be constructed to a bursting pressure of 400 to 500 lbs. on the square inch; and locomotive engine boilers, which are subjected to a much severer duty, to a bursting pressure of 700 to 800 lbs.

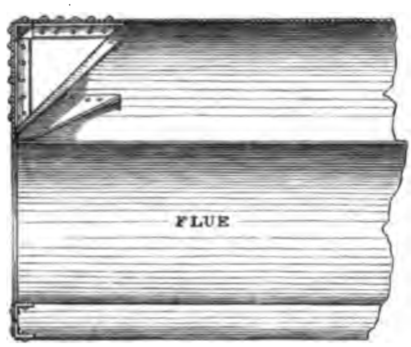
It now only remains for me to state that internal flues, such as contain the furnace in the interior of the boiler, should be kept as near as possible to the cylindrical form: and as wrought iron will yield to a force tending to crush it of about one-half of what would tear it asunder, the flues should in no case exceed one-half the diameter of the boiler; and with the same thickness of plates they may be considered equally safe with the other parts. But the force of compression is so different from that of tension, that I should advise that the diameter of the internal flues be in the ratio of 1 to 2½, instead of 1 to 2, of the diameter of the boiler; if larger, thicker plates must be used.

I will not trouble you with a description of the haycock, hemispherical, and waggon-shaped boilers; they are all bad as respects their powers of resistance, and ought to be entirely exploded; I shall congratulate the public when they disappear from the list of those constructions which have the confidence of the man of science as well as that of the practical engineer.

In conclusion, I have to recommend attention to a few simple

rules, which, if carefully observed, will lead to the most satisfactory results. To construct boilers as nearly as possible of maximum strength, I have already observed that they should be of the cylindrical form; and where flat ends are used, they should be composed of plates one-half thicker than those which form the circumference. The flues, if two in number, to be of the same thickness as the exterior shell; and the flat ends to be of thick plates carefully stayed with gussets of triangular plates and angle-iron, firmly connecting them with the circumference,

Fig. 4.



as in the annexed sketch. I earnestly recommend the use of gussets at *a, a,* as being infinitely better, and more certain, in their action and retaining powers, than stay rods. Gussets, when used, should be placed in lines diverging from the centre of the boiler, and made as long as the position of the flues and other circumstances in the construction will admit. They are of great value in retaining the ends in shape, and may safely be relied upon as imparting an equality of strength to every part of the structure.

I would in conclusion again direct attention to the facts which I have endeavoured to explain. You will, I am persuaded, find them useful; and I trust the objects contemplated by the Committee of your valuable Institution will be fully realized, in the acquisition of greater security and, I trust, in the attainment of a more perfect knowledge of the principles of construction.

LECTURE II.

ON BOILER EXPLOSIONS.

In a former Lecture I endeavoured to explain the principles on which boilers should be constructed, and the laws which govern the strength and other properties of these important vessels. The subject of construction is one of vast importance, and those forms which give the greatest security with the least quantity of material, must embody the true elements of construction, and may be considered as the safest examples for imitation. Boilers, of all other vessels, in the variety of their conditions, shapes, and dimensions, require the head of the philosopher as well as the hands of the mechanic. They contain, within comparatively narrow bounds, a force which, if properly governed, will propel the largest and most stately vessel against wind and tide; perform the work of a thousand hands, and drive a hundred cars loaded with hundreds of tons, at the speed of the swiftest race-horse, from one extremity of the kingdom to the other. They do all this and more; they impart heat and comfort to our dwellings,—are essential in all the requirements of our domestic arrangements,—and under judicious management, advance the interests of commerce, and contribute to the enjoyments of civilized existence.

Reverse the picture, and entrust the construction and management to the hands of incapacity and ignorance, or to the reckless folly and hardihood of fancied security, and death and destruction follow as a result. When the mischief is done, we then

begin to guess at the causes, and to lament the inconsiderate confidence, which led to the employment of incompetency, and to all those errors of construction which invariably present themselves after the event. How often do we hear of the most lamentable accidents terminating in the destruction of life and property, and how often do we lament (when too late) the causes which led to those frightful catastrophes! All these accidents might be prevented, and, instead of using steam, which we now do in our manufactories, at a pressure of 5 to 20 lbs. on the square inch, we might with equal safety use it, and enjoy the advantage of its superior economy, at 60 lbs. on the square inch. It shall be my duty to point out how this may be accomplished, and in these endeavours I hope to have the support of every advocate for increased security to the public, and for a still greater economy in the use of steam.

Before I attempt to give a complete solution to the various problems relative to boiler explosions, I would first direct attention to a few facts which bear more directly upon the question now at issue.

Various notions are entertained as to the causes of boiler explosions, and scientific men are not always agreed as to whether they arise from excessive pressure due to the accumulation of heat, or to some other cause, such as the explosion of hydrogen gas, generated by the decomposition of water suddenly thrown on heated plates. That of the decomposition of water is, I believe, a somewhat prevalent opinion; but I apprehend that this cannot be the invariable cause, inasmuch as in this case we must always assume the boiler to be nearly empty of water, and the plates over the furnace red-hot.

It is not unreasonable that a force so sudden in its origin, and so immediate and destructive in its effects, should suggest the presence of an explosive mixture; but I think it will be difficult, if not impossible, to account for the accumulation of a sufficient quantity of hydrogen, without the presence of oxygen and other gases, in their due proportions, to form an explosive compound. Now as these elements cannot be gene-

rated all at once by the simple decomposition of water (admitting for the moment that the water is decomposed), we must look for some other cause for the fatal and destructive accidents which of late years have become so prevalent.

In treating of this subject, I hope to show not only what are the probable causes of explosions, but that which appears equally important, what are not the causes. So many general theories (some of them exceedingly problematical) have been brought forward on the occasion of disastrous explosions, that we must give the utmost care and attention to all the circumstances of each particular case of explosion before we can decide with a sufficient degree of confidence as to the actual causes tending to produce explosions. To acquire satisfactory evidence as to the precise condition of the boiler and furnace before an explosion, is next to impossible, as most frequently the parties in charge, and from whose mismanagement and neglect we may, in many cases, date the origin of the occurrence, are the first to become the victims of their own indiscretion; and we can only judge from the havoc and devastation that ensue as to the immediate cause of the event.

From this it follows, that in many of the explosions on record, few, if any, of the real circumstances of the cases are made known, and we are left to draw conclusions from the appearances of the ruptured parts, and the terrific consequences which too frequently follow. This want of evidence as to the precise condition of a boiler, with all its valves and mountings, preceding an explosion, is much to be regretted, as it causes a degree of mystery to surround the whole occurrence; and the vague and sometimes inaccurate testimony of witnesses often baffles all attempts at research, and creates additional cause of alarm to all those exposed to the occurrence of similar disasters.

In the discussion of this subject I shall, however, endeavour to trace, from a number of cases in which I have been personally engaged, and from others which have come to my knowledge, the causes which have led to these disastrous effects; and provided that I am successful in the discovery of the true origin

of the majority of those occurrences, we shall have less difficulty in devising and applying the necessary remedies for their prevention.

In my attempts to ascertain facts by a course of reasoning which I shall have to follow in this investigation, I wish it to be understood that it is not my intention to raise doubts and fears in the public mind, calculated to arrest the progress of commercial enterprise, or to cripple the energies of mechanical skill. On the contrary, I am most anxious to promote the advancement of the useful arts, to increase our confidence in the application of increased pressure, and to secure within moderate bounds the economical and useful employment of one of the most powerful agents ever known in the history of practical science. My object in this inquiry will, therefore, be to enlarge our sphere of action by a more comprehensive knowledge of the subject on which it treats; to enforce the necessity of greater caution along with improved construction; and to ensure confidence in all those appliances essential to the public security.

For the attainment of these objects it will be necessary to divide the subject into the following heads:—

1st. Boiler explosions arising from accumulated internal pressure.

2nd. Explosions from deficiency of water.

3rd. Explosions produced from collapse.

4th. Explosions from defective construction.

5th. Explosions arising from mismanagement or ignorance; and

6th. The remedies applicable for the prevention of these accidents.

1st. *Boiler explosions arising from accumulated internal pressure.*

In nine cases out of ten, a continuous increasing pressure of steam, without the means of escape, is probably the immediate cause of explosion; in some instances it arises from deficiency of water, but accidents of this kind are comparatively few in

number, as we often find, in tracing the causes, that they have their origin in undue pressure, emanating from progressive accumulation of steam of great pressure and density. A large boiler under the influence of a furnace in active combustion will generate an immense quantity of steam; and unless this is carried off by the safety-valve or the usual channels when so generated, the greatest danger may be apprehended by the continuous increase of pressure that is taking place within the boiler. Suppose that, from some cause, the steam thus accumulated does not escape with the same rapidity with which it is generated,—that the safety-valves are either inadequate to the full discharge of the surplus steam, or that they are entirely inoperative, which is sometimes the case,—and we have at once the clue to the injurious consequences which, as a matter of fact, are sure to follow. The event may be delayed, and repeated trials of the antagonistic forces from within, and the resistance of the plates from without, may occur without any apparent danger, but these experiments often repeated will at length injure the resisting powers of the material, and the ultimatum will be the arrival of the fatal moment when the balance of the two forces is destroyed, and explosion ensues. How very often do we find this to be the true cause of accidents arising from extreme internal pressure, and how very easily these accidents might be avoided by the attachment of proper safety-valves to allow the steam to escape, and relieve the boiler of those severe trials which ultimately lead to destruction! If a boiler whose generative power is equal to 100, be worked at a pressure of 10 lbs. on the square inch, the area of the safety-valves should also be equal to 100, in order to prevent a continuous increase of pressure; or in case of the adhesion of any of the valves, it is desirable that their areas should, collectively, be equal to 100. If two or more valves are used, 100 or 120 would then be the measure of the outlet*. Under these

* This may be stated in other words, viz. that the generative powers of a boiler being equal to a given number of square inches of area, say 50, the area of the safety-valve should also be 50.

precautions, and with a boiler so constructed, the risk of accident is greatly diminished; and, provided one of the valves is kept in working order, beyond the reach of interference by the engineer, *or any other person*, we may venture to assume that the means of escape are at hand, irrespectively of the temporary stoppage of the usual channels for carrying off the steam.

So many accidents have occurred from this cause—the defective state of the safety-valves—that I must request attention whilst I enumerate a few of the most prominent cases that have come before me. In the year 1845 a tremendous explosion took place at a cotton-mill in Bolton. The boilers, three in number, were situated under the mill, and from the unequal capacity and imperfect state of the safety-valves (as they were probably fast), a terrific explosion of the weakest boiler took place, which tore up the plates along the bottom, and, the steam having no outlet at the top, not only burst out the end next the furnace, demolishing the building in that direction, but tore up the top on the opposite side, and the boiler was projected upwards in an oblique direction, carrying the floors, walls, and every other obstruction before it; ultimately it lodged itself across the railway at some distance from the building. Looking at the disastrous consequences of this accident, and the number of persons (from 16 to 18) who lost their lives on the occasion, it became a subject of deep interest to the community that a close investigation should immediately be instituted, and a recommendation followed that every precaution should be used in the construction as well as the management of boilers.

The next fatal occurrence on record in this district was at Ashton-under-Lyne, where a boiler exploded under similar circumstances, namely from excessive interior pressure, when four or five lives were lost; and again at Hyde, a similar accident occurred from the same cause, which was afterwards traced to the insane act of the stoker or engineer, who prevented all means for the steam to escape by tying down the safety-valve.

There was a boiler explosion at Malaga, in Spain, some years

since, and my reason for noticing it in this place is to show that explosions may be apprehended from other causes than those enumerated in the divisions of this inquiry, and one of these is *incrustation*. Dr. Ritterbrandt says, in a paper read before the Institution of Civil Engineers, by an eminent chemist, Mr. West, "That a sudden evolution of steam under circumstances of incrustation is no uncommon occurrence." In several instances I have known this to be the case, particularly in marine boilers, where the incrustation from salt water becomes a serious grievance, both as regards the duration of the boiler and the economy of fuel.

If it were supposed, as Dr. Ritterbrandt observes, that the boiler was incrusted to the extent of half an inch, it would at once be seen that nothing was more easy than to heat the boiler strongly, even to a red heat, without the immediate contact of water. Under these circumstances, the hardened deposits being firmly attached to the plates, and forming an imperfect conductor of heat, would tend greatly to increase the temperature of the iron, and the difference of temperature thus induced between the iron and the incrustation, and the greater expansibility of the iron, would cause the incrustation to separate from the plates, and the water rushing in between them would generate a considerable charge of highly elastic steam, and thus endanger the security of the boiler.

These phænomena were singularly exemplified in the Malaga explosion, which is thus described by Mr. Hick:—"I have ascertained that a very thick incrustation of salt was formed on the lower part of the boiler, immediately over the fire, and so far as it extended the plates appear to have been red-hot, being thereby much weakened, and hence the explosion. The ordinary working pressure of the boiler is 130 lbs. per square inch, and perhaps at the time of the explosion very much above that pressure, as there was only one small safety-valve of two and a half inches diameter. The boiler was only 2 feet 6 inches diameter, and 20 feet long."

Incrustation, exclusively of being dangerous, is attended with

great expense and injury to the boiler in its removal. In the case of the transatlantic, oriental, or other long sea-going vessels, even after the use of brine-pumps, blowing out, &c., a very large amount of incrustation is formed, and considerable sums of money are expended each voyage to remove it.

Other explosions of a more recent date are those which occurred at Bradford and Halifax. They are still fresh in the recollection of the public mind, and are so well known as not to require notice in this place*.

I cannot, however, leave this part of the subject without reverting to an accident which occurred on the Lancashire and Yorkshire Railway, which had its origin in the same cause—excessive internal pressure. This accident is the more peculiar as it led to a long mathematical disquisition as to the nature of the forces which produced results at once curious and interesting. The conclusions at which I arrived, although *practically right, were, however, considered by some mathematically wrong*, as they were firmly combated by several eminent mathematicians; but notwithstanding the number of algebraic formulæ, and the learned discussions of my friends on that occasion, I have been unable to change the opinions I then formed.

The accident here alluded to occurred to the "Irk" locomotive engine, which in February 1845 blew up and killed the driver, stoker, and another person who was standing near the spot at the time. A great difference of opinion as to the cause of this accident was prevalent in the minds of those who witnessed the explosion, some attributing it to a crack in the copper fire-box, and others to the weakness of the stays over the top. Neither of these opinions was, however, correct, as it was afterwards demonstrated that the material was not only entirely free from cracks and flaws, but the stays were proved sufficient to resist a pressure of 150 to 200 lbs. on the square inch. The true cause was afterwards ascertained to arise from the fastening

* Since the above was written another terrific explosion has taken place at Rochdale, accompanied with great loss of life. See Report on the Rochdale Boiler Explosion, July 15th, 1854. Appendix No. III.

down of the safety-valve of the engine (an active fire being in operation under the boiler at the time), which was under the shed, with the steam up, ready to start with the early morning train. The effect of this was the forcing down of the top of the copper fire-box upon the blazing embers of the furnace, which, acting upon the principle of the rocket, elevated the boiler and engine of 20 tons weight to a height of 30 feet, which, in its ascent, made a summersault in the air, passed through the roof of the shed, and ultimately landed at a distance of 60 yards from its original position. The question which excited most interest, was the absolute force required to fracture the fire-box, its peculiar properties when once liberated, and the elastic or continuous powers in operation, which forced the engine from its place to an elevation of 30 feet from the position in which it stood. An elaborate mathematical discussion ensued relative to the nature of these forces, which ended in the opinion that a pressure sufficient to rupture the fire-box, was, by its continuous action, sufficient to elevate the boiler and produce the results which followed. Another reason was assigned, namely, that an accumulated force of elastic vapour, at a high temperature, with no outlet through the valves, having suddenly burst upon the glowing embers of the furnace, would charge the products of combustion with their equivalents of oxygen, and hence explosion would follow. Whether one or both of these two causes were in operation is difficult to determine; at all events, we have in many instances precisely the same results produced from similar causes, and unless greater precaution is used in the prevention of excessive pressure, we may naturally expect a repetition of the same fatal consequences.

The preventives against accidents of this kind are, well constructed boilers of the strongest form, and duly proportioned safety-valves; one under the immediate control of the engineer, and the other, as a reserve, under the keeping of some competent authority.

2nd. *Explosions from deficiency of water.*

This division of the subject requires the utmost care and

attention, as the circumstance of boilers being short of water is no unusual occurrence. Imminent danger frequently arises from this cause; and it cannot be too forcibly impressed upon the minds of engineers, that there is no part of the apparatus constituting the mountings of a boiler which requires greater attention—probably the safety-valves not excepted—than that which supplies it with water. A well-constructed pump, and self-acting feeders, when boilers are worked at a low pressure, are indispensable; and where the latter cannot be applied, the glass tubular gauge, steam, and water-cocks must have more than ordinary attention.

In a properly constructed boiler every part of the metal exposed to the direct action of the fire should be in immediate contact with the water, and when proper provision is made to maintain the water at a sufficient height above the plates so exposed, accidents can never occur from this cause.

Should the water, however, get low from defects in the pump, or any stoppage of the regulating feed-valves, and the plates over the furnace become red-hot, we then risk the bursting of the boiler, even at the ordinary working pressure. We have no occasion, under such circumstances, to search for another cause, from the fact that the material when raised to a red heat has lost about five-sixths of its strength, and a force of less than one-sixth will be found amply sufficient to bear down the plates direct upon the fire, or to burst the boiler.

An erroneous opinion has gone abroad that boilers are burst from the production of hydrogen gas, and that when suddenly replenished with water when the plates are in a state of incandescence or red-hot. Now there cannot be a greater fallacy than this, as it can be shown that water poured upon hot plates in a close vessel resolves itself into steam; the experiments of the Committee of the Franklin Institute, as well as the evidence of Mr. Pearsall—a pupil of Faraday's—given in his examination at Hull on the bursting of the Union Steam Packets boiler, confirm this opinion. That gentleman states, that "in his opinion it could not have taken place, if the boiler had been sufficiently

supplied with water, unless the steam generated was prevented escaping by some great force which would hold the safety-valve fastened down or obstructed. I consider the immediate cause of the bursting of the boiler to have been the expansive power of steam, because steam is capable of producing any such effects. I am most decidedly of opinion that it did not arise from gas. My reasons for that opinion are, that although water is decomposed rapidly by red-hot iron, yet it requires that the surface of the iron should be in a metallic state; a new boiler is nearly in that condition, but not quite so; there is just the chance that if a new boiler were employed, and any pure water admitted in small quantity, so as to allow portions of the boiler to become red-hot, then water might become decomposed; but such circumstances would at the same time be sufficient to generate an incalculable amount of steam. Such explosion, therefore, would arise from mixed causes—such as the presence of the gas, and the enormous amount of steam and its great pressure. I cannot suppose a case where such decomposition of water and evolution of gas would take place, where such water is employed as that of the Humber, or as that furnished by the ocean. Such gas would not be inflammable of itself; there must be the presence of atmospheric air or oxygen, and of flame or a substance heated to a very high degree."

Such are the opinions of a gentleman whose education and pursuits enabled him to arrive at a correct conclusion; and I am firmly persuaded that no explosion can possibly take place from the production of hydrogen gas, even assuming this to occur, without its equivalent of atmospheric air or oxygen. In a close vessel, such as a boiler, atmospheric air is inadmissible; and how is it possible that an explosive mixture can be formed under circumstances so extremely adverse to such an hypothesis? In fact, I am of opinion that we have no foundation for such a theory, nor have we the least shadow of evidence to prove the presence of hydrogen gas in a boiler.

When a boiler becomes short of water, the first, and perhaps the most natural act, is to run to the feed-valve and pull it

wide open. This certainly remedies the deficiency, but increases the danger, by suddenly pouring upon the incandescent plates a large body of water, which, coming in contact with a reservoir of intense heat, is calculated to produce highly elastic steam. This has been hitherto controverted by several eminent chemists and philosophers; but I make no doubt that such is the case, unless the pressure has forced the plates into a concave shape, which for a time would retard the evaporization of the water when suddenly thrown upon them. Some curious experimental facts have been elicited on this subject, and those of M. Boutigny, and Professor Bowman, of King's College, London, show that a small quantity of water projected upon a hot plate does not touch it; that it forms itself into a globule surrounded with a thin film, and rolls about upon the plate without the least appearance of evaporation. A repulsive action takes place, and these phænomena are explained upon the supposition that the spheroid has a perfectly reflecting surface, and consequently the heat of the incandescent plate is reflected back upon it. What is, however, the most extraordinary in these experiments, is the fact that the globule, whilst rolling upon a red-hot plate, never exceeds a temperature of about 204° of Fahrenheit; and in order to produce ebullition, it is necessary to cool the plate until the water begins to boil, when it is rapidly dissipated in steam.

The experiments by the Committee of the Franklin Institute on this subject, give some interesting and useful results. That Committee found that the temperature at which clean iron vaporized drops of water, was 334° Fahrenheit. The development of a repulsive force which I have endeavoured to describe was, however, so rapid above that temperature, that drops which required but one second of time to disappear at the temperature of maximum vaporization, required 152 seconds when the metal was heated to 395° of Fahrenheit. The Committee go on to state that "One ounce of water introduced into an iron bowl three-sixteenths of an inch thick, and supplied with heat by an oil-bath, at the temperature of 546°, was vaporized in fifteen

seconds, while at the initial temperature of 507°, that of the most rapid evaporization was thirteen seconds."

The reduction of the temperature of the metal is here followed by an increase in the rapidity of the evaporization, which by a reduction of 38° is effected in thirteen seconds instead of fifteen seconds.

This does not, however, hold good in every case, as an increased quantity of water, say from one-eighth of an ounce to two ounces, thrown upon heated plates, raised the temperature of vaporization from 460° to 600° Fahrenheit; thus clearly showing that the time required for the generation of explosive steam under these circumstances is attended with danger; and it may be doubted whether the ordinary safety-valves are fully adequate for its escape.

Numerous examples may be quoted to show that explosions from deficiency of water, although less frequent than those arising from undue pressure, are by no means uncommon. They are nevertheless comparatively few in number, and the preventives are good pumps, self-acting feeders (when they can be applied), and all those boiler appendages, such as water cocks, water gauges, floats, alarms, and other indicators of the loss and reduction of water in the boiler.

3rd. *Explosions produced from collapse.*

Accidents from this cause can scarcely be called explosions, as they arise, not from internal force which bursts the boiler, but from the sudden action of a vacuum within it. In high-pressure boilers, from their superior strength and circular form, these accidents seldom occur, and the low-pressure boiler is effectually guarded against it by a valve which opens inwards by the pressure of the atmosphere whenever a vacuum occurs. In some cases a collapse of the internal flues of boilers has been known to take place, from a partial vacuum within them, which, united to the pressure of the steam, has forced down the top and sides of the flue, and with fatal effect discharged the contents of the boiler into the ash-pit, and destroyed and scalded everything before it. A circumstance of this kind occurred on

the Thames on board the steamer *Victoria*, some years since, when a number of persons lost their lives, and serious injury was sustained by persons in all parts of the vessel within reach of the steam. This accident could not, however, be called an explosion, but a collapse of the internal flues, which were of large dimensions, and the consequent discharge of large quantities of steam and water into the space occupied by the engines.

One or two cases which bear more directly on this point are, however, on record, and one of them, which took place in the Mold mines, in Flintshire, was attended with explosion. The particulars, as given by Mr. John Taylor, will be found circumstantially recorded in the first volume of the Philosophical Magazine, 2nd ser., p. 126. This occurrence seems to prove that rarefaction produced in the flues of a high-pressure boiler may determine an explosion. The boiler which exploded belonged to a set of three boilers which feed the same engine; the fuel used was bituminous coal. The furnace-doors of all three of the boilers had been opened, and the dampers of two had been closed, when a gust of flame was seen to issue from the mouth of the furnace of these latter, and was immediately followed by an explosion. The interior flue of this boiler was flattened from the sides, the flue and shell of the boiler remaining in their places, and the safety-valve upon the latter not being injured.

Similar cases of collapse might be mentioned, but as most of them were attended by a defective supply of water in the boiler, the plates over the fire having become heated, they can scarcely be included in the category of this class of accidents, and more properly belong to those of which we have just treated,—explosions from a deficiency of water in the boiler.

It is nevertheless necessary to observe, that cases of collapse should be carefully guarded against, as the great source of danger is in the escape of hot water, which, with the steam generated by it, produces death in one of its worst and most painful forms.

The remedies for these accidents will be found in the vacuum

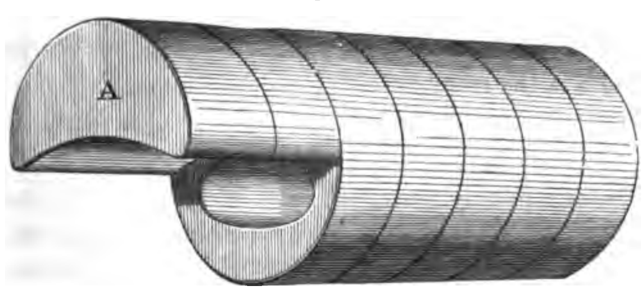
valve, and in the careful construction of the flues with respect to their form as well as their strength.

4th. *Explosions from defective construction.*

This is perhaps one of the most important divisions that can possibly engage our attention, and on which it shall be my duty to enlarge. In a previous inquiry, I have already shown the nature of the strain which boilers undergo, and the ultimate resistance which the material used in their construction is able to bear. We have not, however, in all cases, shown the distribution and position in which that material should be placed in order to attain the maximum of strength, and to afford to the public the greatest security in the resisting powers of vessels subject to severe and sometimes ruinous pressure. This is a subject of such importance that I shall be under the necessity of trespassing upon your time, in endeavouring to point out the advantages peculiar to form, and to the use of a sound and perfect system of construction.

For a number of years the haycock, hemispherical, and waggon-shaped boilers were those generally in use; and it was not until high-pressure steam was first introduced into Cornwall, that the cylindrical form with hemispherical ends, and the furnace under the boiler, came into use. Subsequently this gave way to the introduction of a large internal flue extending the whole length of the boiler, and in this the furnace was

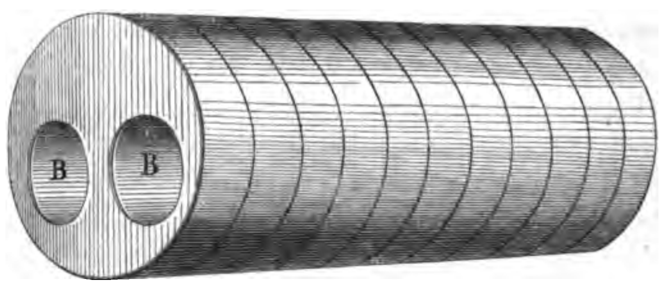
Fig. 5.



placed. For many years this was the best and most economical boiler in Cornwall, and its introduction into this country has

effected great improvements in the economy of fuel as well as in the strength of the boiler. Several attempts have been made to improve this boiler by cutting away one-half of the end, in order to admit a larger furnace. This was first done by the Butterley Company, and it has since gone by the name of the Butterley boiler. This construction has the same defects as the haycock or *hemispherical* and waggon-shaped boilers; it is weak over the fire-place, and cannot well be strengthened without injury to the part A, fig. 5, of the boiler, from the vast number of stays necessary to suspend the part which forms the canopy of the furnace. Of late years a much greater improvement has, however, been effected by the double flue, BB, fig. 6, and double

Fig. 6.



furnace boiler, which is now in general use, and has nearly superseded all the other constructions. It consists of a cylinder, varying from 5 to 7 feet in diameter, with two flues which extend the whole length of the boiler; they are perfectly cylindrical, and of sufficient magnitude to admit a furnace in each. This boiler is the simplest, and probably the most effective, that has yet been constructed. It presents a large flue surface as the recipient of heat, and the double flues, when riveted to the flat ends, add greatly to the security and strength of those parts. It moreover admits of the new process of alternate firing, so highly conducive to perfect combustion, and the prevention of the nuisance of smoke.

Another boiler, into which a number of small tubes are introduced, exhibits a powerful generator of steam, from the

extent of its flue surface, and the facility with which the repairs can be effected. It does not present any greater security against explosion than the boiler with two flues, but its construction on the tubular system effects a great saving in space, and is otherwise productive of all the advantages of economy in the consumption of fuel and the prevention of smoke. This boiler is constructed with a large internal flue, divided in the middle, which admits of two fire-places and alternate firing. In the space which I call the mixing chamber the products of combustion amalgamate, and are thus ignited before they enter the tubes, and from which they issue into the end flues, and from thence to the chimney in the usual way. In this respect it will be observed that the boiler has the same form as the boiler last described, and contains the same elements of strength as the double-flue boiler, the only difference being a combination of the locomotive and marine tubular system, which contains a large absorbent heating surface in a small space*.

It will not be necessary to multiply examples of construction, as I have already described those which I consider best calculated to sustain severe pressure. When the parts of these boilers are judiciously and skilfully arranged, with a grate bar surface well proportioned to the amount of flue surface as the recipient, we may reasonably conclude that we are not far from the maximum of strength, including other important elements in the material, and the consumption of fuel.

The means necessary to be employed in this department of the inquiry for the prevention of accidents, are a knowledge of

* In some cases it has been found necessary to extend the circulation of the heated currents, as they issue from the tubes, round the boiler in the usual way, in order to prevent the escape of too much heat up the chimney. This shows that the recipient surface of the tubes is insufficient under the process of active combustion, and is probably another reason for the introduction of increased boiler surface; it being evident that time is an important element in the process of economical working; and provided this has to be accomplished, the absorbent surfaces must be enlarged to the extent of reducing the temperature of the heated products as they leave the boiler to 500° or 600° of Fahrenheit.

the principles of construction, and an acquaintance with the strength and properties of the materials used for that purpose.

5th. *Explosions arising from mismanagement or ignorance.*

To mismanagement, ignorance, and the misapplication of a few leading principles in connexion with the use and application of steam, may be traced the great majority of accidents which from time to time occur. Many of these accidents, so fruitful in the destruction of property and human life, might be prevented, if we had well-constructed vessels, judiciously united to skill and competency in the management. To convey a few practical instructions to engineers, stokers, and engine-men, would be an undertaking of no great difficulty. A young man of ordinary capacity would learn all that is necessary in a few months; and if placed under competent instructors, he might be made acquainted with the properties of steam,—its elastic force at different degrees of pressure,—the advantages peculiar to sensitive and easy-working safety-valves,—the necessity for keeping them clean and in good working condition,—the use of water gauges, fusion plugs, indicators, signals, &c., &c., as connected with the supply and height of water in the boiler,—the dangers to be apprehended from a scarcity of water,—the danger of explosion when the engine is standing, or when the usual channels for relieving the boiler of its surplus steam are stopped. The stoker, as well as the engineer, should be thoroughly acquainted with all these parts of elementary instruction; and no proprietor of a mill, captain of a steam-ship, or superintendent of locomotives, should give employment to persons unless they can produce certificates of good behaviour, and a knowledge of these and other elementary principles of their profession.

If these precautions were adopted, and greater care observed in the selection of men of skill and responsibility in the construction of boilers, together with a more strict and rigid code of laws in the management of the engine, we might look forward with greater certainty to a considerable diminution, if not a prevention, of those calamitous events which so frequently plunge whole families into mourning by unexpected and instantaneous death.

As an individual duty, I would cheerfully lend my best assistance to the development of a sound principle of instruction calculated to relieve the country of the ignorance which pervades that part of the community on which the lives of so many depend. A resolution on the part of those who employ persons of this description, and whose interests are so much at stake, to employ only those persons whose knowledge and character come up to the requisite standard, and to pay them adequately, would soon produce, from the economy of the management and the increased security of the property, the most satisfactory results. How often do we find implements of danger, and vessels containing the elements of destruction, in the hands of the most ignorant and reckless practitioners, whose insensibility to danger, and total incompetency to judge of its presence, render them above all others the most unfit to be employed! And why? Because they are the very persons, from their defective knowledge, to increase the danger and aggravate the evils they were selected to prevent. It is not the first time that engineers, to secure (if I may use the expression) an insane pressure, have fastened the safety-valves, and screwed down the steam-valve, closing every outlet, without ever thinking of the fire that was blazing under the boiler. Under such circumstances what could be expected but a blow-up? A madman rushing with a lighted match into a powder magazine could not act with greater insanity. Such, however, has been the case, and this has resulted from want of thought, or what is worse, from the total absence of that kind of knowledge which the employer as well as the workman should always possess.

I have on former occasions stated that I am not an advocate for legislative interference either in the construction or management of boilers; but seeing the dangerous tendency of these vessels when placed under the control of ignorance and incapacity, I would forego many considerations in order to secure the services of a more judicious and intelligent class of men than has hitherto been employed in the care and management of steam and the steam-engine. The reforms necessary to be intro-

duced may be made by the owners of steam-engines, steam-boats, railways, and others engaged in the use and application of this important element. A desire to enforce more judicious and stringent regulations, to remunerate talent, and to employ only those whose good conduct and superior knowledge entitle them to confidence, is the only sure guarantee of public safety and the prosperity of the employer.

Lastly, *The remedies applicable for the prevention of accidents arising from explosions.*

Having noticed in the foregoing heads most of the causes tending to produce boiler explosions, it now only remains for us to draw such inferences as will enable us to point out the circumstances which it is desirable to cultivate, and those which it is desirable to avoid. These circumstances I have endeavoured to class in such a way as to bring the subject prominently forward, and to point out under each head, first, the causes which lead to accident; and secondly, the means necessary to be observed in avoiding it. In a general summary it may not be inexpedient briefly to recapitulate these statements, in order to impress more forcibly upon the mind of those concerned, the necessity for care and consideration in the use of one of the most powerful agents ever placed at our disposal.

One of the most scientific nations of Europe places the greatest confidence, as a means of safety, in the use of a fusible metal plate over the furnace. These plates are alloys of tin and lead, with a small portion of bismuth, in such proportions as will ensure fusion at a temperature something below that of molten lead. In France the greatest importance is attached to these alloys, and in order to ensure certainty as to the definite proportions, the plates are prepared at the Royal, now the Imperial Mint, where they may be purchased duly prepared for use. In this country these alloys are not generally in use, but in this respect I think we are wrong, as boiler explosions are not so frequent in France as in this country, and high-pressure steam, from its superior economy, is more extensively used in France than in England. In my own practice I invariably insert a lead

rivet, one inch in diameter, immediately over the fire-place, and as lead melts at 640°, I have invariably found these metallic plugs a great security in the event of a scarcity of water in the boiler. I am persuaded many dangerous explosions may be avoided by the use of this simple and effective precaution; and as pure lead melts at 600°, we may infer from this circumstance that notice will be given and relief obtained before the internal pressure of the steam exceeds that of the resisting powers of the heated plates. As this simple precaution is so easily accomplished, I would advise its general adoption. It can do no harm to the boiler, and may be the means of averting explosions and the destruction of many valuable lives.

The fusible metal plates, as used in France, are generally covered by a perforated metallic disc, which protects the alloy of which the plate is composed, and allows it to ooze through as soon as the steam has attained the temperature necessary to ensure the fusion of the plate. The nature of the alloy is, however, somewhat curious, as the different equivalents have different degrees of fluidity, and the portion which is the first to melt is found out by the pressure of the steam causing the adhesion of the less fusible parts, but in a most imperfect state, and incapable of resisting the internal force of the steam. The result of these compounds is, the fusion of one portion of the alloy and the fracture of the other, which is generally burst by pressure.

This latter description of fusible plate is different to the lead plug over the fire, which is fused at 600° by the heat of the furnace, and the other, by the temperature of the steam, when raised to the fusible point of the alloy, which varies from 280° to 350°.

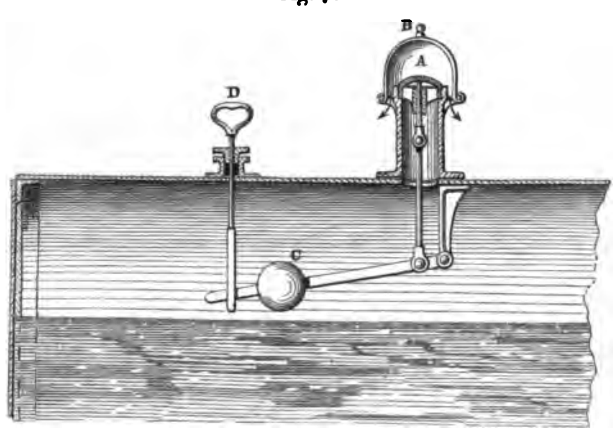
Another method is the bursting plate, fixed in a frame and attached to some convenient part of the upper side of the boiler; this plate should be of such thickness and of such ductility as to cause rupture whenever the pressure exceeds that of the weight on the safety-valve. There can be no doubt that such an apparatus, if made with a sufficiently large opening, would

relieve the boiler; but the objections to this and several other devices are the frequent bursting of those plates, and the effect which every change of pressure has upon the material in reducing its powers of resistance, and thus increasing the uncertainty as to the amount of pressure in the boiler; besides, there is the expense and loss of time connected with the renewal of the plates.

It has already been noticed that one of the most important securities against explosions is a duly proportioned boiler, well constructed; and to this must be added ample means for the escape of the steam on every occasion when the usual channels have been suddenly stopped. The only legitimate outlets under these circumstances appear to me to be the safety-valves, which, connected with this inquiry, are indispensable to security. Every boiler should therefore have two safety-valves, any one of them of sufficient capacity to carry off the quantity of steam generated by the boiler. One of these valves should be of the common construction, and the other beyond the reach of the engineer or any other person.

[Fig. 7 is a sketch of a lock-up safety-valve, as constructed by Mr. Fairbairn. A is the valve. B is a shell of thin brass,

Fig. 7.



opening on a hinge and secured by a padlock; it is of such a diameter as to allow the waste steam to escape in the direction

of the arrows. C is the weight, which may be fixed at any part of the lever, to give the desired amount of pressure, but which cannot be fixed or altered unless the boiler is opened to allow a man to get inside. D is a handle, having a long slot, by which the valve may be relieved or tried at any time, to obviate the liability of its corroding or being jammed; the engineer cannot, however, put any additional weight upon the valve by this handle.]

Whilst tracing the causes of explosions from a deficiency of water in the boiler, I have recommended as the usual precautions, good pumps, self-acting feeders, water cocks, glass gauges, floats, alarms, and other indicators which mark the changes and variation in the height of the water. To these may be added the steam whistle, but, above all, the constant inspection of a careful, sober, and judicious engineer. Above all other means, however ingeniously devised, this is the most essential to security, for on that official depend, not only the security of the property under his charge, but also the interests of his family, and the lives of all those within the immediate influence of his operations. One of the most important considerations in this and every other department of management is cleanliness and the careful attention of a good engineer.

Explosions produced from collapse have their origin in causes entirely different from those which arise from a deficiency of water, and the only remedy that can be applied is the vacuum valve and the cylindrical or spheroidal form of boiler.

Defective construction is unquestionably one of the greatest sources of the frightful accidents which we are so frequently called upon to witness. No man should be allowed unlimited exercise of judgment on a question of such vital importance as the construction of a boiler, unless he is duly qualified by matured experience in the theoretical and practical knowledge of form, strength of materials, and other requirements requisite to ensure the maximum of sound construction. It appears to me equally important that we should have the same proofs and acknowledged system of operations in the construction of boilers,

that we have in the strength and proportions of ordnance. In both cases we have to deal with a powerful and dangerous element; and I have yet to learn why the same security should not be given to the general public as we find so liberally extended to an important branch of the public service. In the ordnance department at Woolwich (with which I have been more or less connected for some years) the utmost care and precision are observed in the manufacture of guns; and the proofs are so carefully made under the superintendence of competent officers, as to render every gun perfectly safe to the extent of 1000 to 1200 rounds of shot.

Boilers and artillery are equally exposed to fracture, and it appears to me of little moment whether the one is burst by the discharge of gunpowder, or the other by the elastic force of steam.

Taking into consideration all the circumstances connected with the bursting of boilers and the bursting of guns, and looking at the active competition which exists, and is likely to be extended, in manufactures, railway traffic, and steam navigation, rendering it every day more desirable to reduce the cost by an extended use of steam at a much higher pressure, it surely becomes a desideratum to secure the public safety by the introduction of some generally acknowledged system of construction that will bear the test of experience, and involve a maximum power of resistance. The most elaborate disquisitions have been given, by the most distinguished men of all ages, since the invention of gunpowder, to discover the strength and form of guns of every description. Surely boilers are equally if not more important, as the sacrifice of human life appears to me to be much greater in the one case than in the other. It would be a matter of paramount importance to the public, if men, combining the greatest practical skill with the highest scientific attainments, would give such an *undeniable security* to boilers, as to ensure them capable of bearing, under the most unfavourable contingencies, at least *six times* their working pressure.

On the question of explosions arising from mismanagement and ignorance, I have little further to add; but I must again observe, that the subject of security from boiler explosions is of such importance as to call for more able exponents than myself. I have endeavoured to trace the causes of these lamentable occurrences, and to draw such deductions therefrom as I trust may be useful in at least mitigating, if not almost entirely averting, the danger.

I have endeavoured to show that the precautions necessary to be observed in the construction and management of boilers are as follows:—

1st. To avoid explosions from internal pressure, cylindrical boilers of maximum form and strength must be used, including all the necessary appendages of safety-valves, &c.

2nd. Explosions arising from deficiency of water may be prevented by the fusible alloys, bursting plates, good feed-pumps, water gauges, alarms, and other marks of indication; but above all, the experienced eye and careful attention of the engineer is the greatest security.

3rd. Explosions from collapse are generally produced from imperfect construction, which can only be remedied by adopting the cylindrical form of boiler, and a valve to prevent the formation of a vacuum in the boiler.

4th. Explosions from defective construction admit of only one simple remedy, and that is, the adoption of those forms which embody the maximum powers of resistance to internal pressure, and such as we have already recommended for general use.

Lastly. Good and efficient management, a respectable and considerate engineer, and the introduction of such improvements, precautions, and securities as we have been able to recommend, will not only ensure confidence, but create a better system of management in all the requirements necessary to be observed for the prevention of steam-boiler explosions.

In conclusion, I may observe, that in giving evidence before the jury in the case of the Rochdale explosions (Appendix No. IV.), I took occasion to recommend the formation of an Association

for the exclusive purpose of watching over the interests of the proprietors of steam-boilers, not only with respect to the prevention of explosions and the attainment of the greatest security, but also with respect to the organization of a better system of management for the raising of steam with the greatest economy. Fortunately for the public security, and probably for the benefit of all the parties concerned, that recommendation has had the desired effect, and an Association has been formed in the Manchester district of the manufacturers, with the unanimous consent of the great majority of mill-owners, for the accomplishment of these objects.

This Association was instituted at a meeting of the employers of steam-boilers, favourable to the objects proposed, on the 23rd of January last, 1855. It is under the management of a Committee and a General Inspector, Mr. R. Longridge, and its primary object is to secure the greatest practical safety in the raising and use of steam, by means of an intelligent supervision, to be carried on by competent and well-instructed inspectors, employed by the Association; but in addition to this inspection for the purpose of safety, the rules provide for a *permissive* supervision of furnaces, and for a record, *with the consent of the owners*, of the duty performed by the steam-engines, and the amount of the fuel consumed, with a view to a more perfect combustion and greater economy in fuel. And this supervision will be extended to the establishments of all the members who do not object to this branch of the Association's operations.

The principal object contemplated by the formation of this Association is, however, increased security against *explosions*, which a periodical inspection by an experienced engineer affords, and in the saving of fuel which may be expected, under the inspection of an intelligent officer well acquainted with the principle on which perfect combustion depends, and with the most successful modes of applying those principles in practice; to which may be added, the removal of any pretence for Government inspection.

The two following papers formed the substance of a Report

prepared at the request of the British Association for the Advancement of Science. It was read at the meeting held at York in September 1844, and published in the Transactions for that year. I now present them in the form of Lectures, including all those improvements and experiments that have been made in this important and difficult question since their first publication. This abstract does not profess to be an enlarged view of the subject, but it embodies many useful suggestions, and will enable the reader to form an opinion as to what has been done, and what may yet be accomplished, in establishing sound principles of action relative to the economic value of our mineral fuel.

LECTURE III.

ON THE CONSUMPTION OF FUEL AND THE PREVENTION OF SMOKE.

THERE is, perhaps, no subject so difficult, and none so full of perplexities, as that of the management of a furnace and the prevention of smoke. I have approached this inquiry with considerable diffidence, and after repeated attempts to derive some definite conclusions, I have more than once been forced to abandon the investigation as inconclusive and unsatisfactory. The difficulties of the question do not arise from any defect in our acquaintance with the laws which govern perfect combustion, the economy of fuel, or the consumption of smoke. They chiefly arise from the constant change of temperature, the variable nature of the volatile products, the want of system, and the irregularity which attends the management of the furnace, and above all, from the want of some acknowledged system for bringing a due proportion of air in contact with the combustible gases in the proper manner. Habits of economy and attention, with regard to a few simple and effective rules, are either entirely neglected or not sufficiently enforced, and it appears obvious to every observer that much has yet to be done, and much may yet be accomplished, provided the necessary precautions are taken, first to establish, and next to carry out, a comprehensive and well-organized system of operations. If this were accomplished, and the management of the furnace consigned to men of more intelligence, properly trained in relation to their respective duties, all these difficulties would vanish, and the public might not only look forward with confidence to the working of our engines in the manufacturing towns, but the proprietors of steam-engines would be more than compensated for their additional expenditure by the saving of fuel

which the improved system of management would ensure. Under the hope of attaining these objects, I shall endeavour to show, from a series of accurately conducted experiments, that the prevention of smoke, and the perfect combustion of fuel, are synonymous, and completely within the reach of all those who choose to adopt measures calculated for the suppression of the one, and the improvement of the other.

On a former occasion I had the honour of presenting to the British Association an inquiry into the merits of Mr. C. W. Williams's Argand furnace, as compared with those of the usual construction. On that occasion it was found, from an average of a series of experiments, that the saving of fuel (inclusive of the absence of smoke) was in the ratio of 292 to 300, or as 1 : 1·039; being at the rate of 4 per cent. in favour of Mr. Williams's plan. Since then a considerable number of experiments have been made by Mr. Houldsworth, Mr. Williams, and others; and having occasion in the course of this inquiry to refer to these researches, it will be unnecessary for the present to notice them further than to observe, that they have been made with great care, and that they present some curious and interesting phænomena in connexion with the further development of this subject.

The complex nature of the investigation has rendered it necessary to divide the subject into sections, for the purpose of observing, not only the relative tendencies and connexion of each, but to determine, by a series of comparative results, the law on which perfect combustion is founded, and its practical application ensured.

Keeping these objects in view, the heads of inquiry will be in this and the next Lecture,—

I. The analysis or constituents of coals and other fuels.

II. The relative proportions of the furnace, and forms of boilers.

III. The temperature of the furnace and surrounding flues.

IV. The economy of fuel, concentration of heat, and prevention of smoke.

Lastly. General summary of results.

I. *The constituents of coals and other fuels.*

The first practical inquiries into the nâture and constituents of coal, are probably those of Dr. Thomson and Mr. Mushet; several others have investigated their chemical composition, but the discrepancies which exist in the varied forms of analysis render them of little value when applied to the useful arts. Dr. Thomson examined four distinct species of coal, of which the following are the results:—

Quality.	Specific gravity.	Carbon.	Hydrogen.	Azote.	Oxygen.
Caking coal	1·269	75·28	4·18	15·96	4·58
Splint coal...............	1·290	75·00	6·25	6·25	12·50
Cherry coal	1·263	74·45	12·40	10·22	2·93
Cannel coal	1·272	64·72	21·56	13·72	...

Dr. Ure also supplies an analysis of splint and cannel coal, which differ from those experimented upon by Dr. Thomson, as follows:—

Quality.	Specific gravity.	Carbon.	Hydrogen.	Azote.	Oxygen.
Splint coal...............	1·266	70·90	4·30	...	24·80
Cannel coal	1·228	72·22	3·93	2·8	21·05

The chief difference between the experiments seems to consist in the increased quantity of hydrogen in Dr. Thomson's cannel coal, and the total absence of oxygen, which in Dr. Ure's specimens was found in excess.

The next authority is Mr. Mushet, who analysed nearly the whole of the Welsh coals, and some others, of which the following are selected, viz.—

Quality.	Specific gravity.	Carbon.	Ashes.	Volatile matter.
Welsh furnace coal	1·337	88·068	3·432	8·300
Welsh stone coal	1·393	89·700	2·300	8·000
Welsh slaty coal	1·409	82·175	6·725	9·100
Derbyshire furnace coal ...	1·264	52·882	4·288	42·830
Derbyshire cannel coal......	1·278	48·362	4·638	47·000

Again, we have some of the American anthracites, with upwards of 90 per cent. of carbon and 3·6 of volatile matter, which correspond with nearly all the other descriptions of anthracites as given by Mr. Mushet, and more recently by Dr. Kane, in his excellent work 'On the Industrial Resources of Ireland.'

In addition to the above, Dr. Fife has given some valuable experiments on coal, wherein he does not materially differ in the bituminous qualities from those of Mr. Mushet. The results of Dr. Fife's experiments were found to be in the bituminous and anthracite kinds:—

	Bituminous.	Anthracite.
Moisture	7·5	4·5
Volatile matter	34·5	13·3
Fixed carbon	50·5	71·4
Ashes	7·5	10·8
	100·0	100·0

It will be observed from these experiments that considerable differences exist as to the quantity of carbon contained in each sort; and provided it be correct that the heating power of any description of fuel is in proportion to the quantity of carbon it contains, it then follows that the anthracite must be greatly superior to the bituminous qualities, which yield little more than one-half the quantity of carbon. Considerable difficulty is, however, encountered in the combustion of the anthracite coal, as intense heat is not only an element, but time, and a large quantity of oxygen, are absolutely necessary to volatilize its products. It has been known to pass twice through an iron smelting furnace, and subjected for upwards of forty hours to the temperature of melting iron, without being affected beyond the exterior surface, having been calcined to a depth of not more than three-fourths of an inch. Such, however, is the obduracy of its character, that intense heat makes little or no impression upon it. To burn anthracite coal effectually, and to extract the whole

of its volatile products, it must be broken into small pieces, and thrown upon a furnace having a large supply of oxygen passing continually through it.

In the combustion of bituminous coal the operation is totally different, being partly friable, and splitting into fragments as the gases are evolved; and hence arises the superior value of this description of fuel in almost every branch of the industrial arts.

The Newcastle, and the best qualities of the Durham coal, are exceptions to most others of the bituminous kind; they contain a much greater quantity of carbon, and are thus better fitted for the furnace. From some accurate experiments by Mr. Richardson they are found to contain:—

Carbon	85·613	Specific gravity 1·278.
Hydrogen	5·205	
Azote and oxygen	7·226	
Ashes	1·956	
	100·000	

The Lancashire coals approach nearer to the Newcastle and Durham than most others; and, taking the mean of some recent experiments, they contain:—

Carbon	82·95
Hydrogen	5·86
Azote and oxygen	7·93
Ashes	3·26
	100·00

The specific gravity of the Lancashire coal is rather more than that of the Newcastle coal, but in other respects their constituents are much alike, with the exception of a greater proportion of ashes in the former than is found in the finer qualities of the latter.

Dr. Kane, in his recent work 'On the Industrial Resources of Ireland' (already alluded to), has given some valuable information on the properties of the Irish anthracites and other coals found in different districts of the country. He also ascertained the value of the different beds of lignite which retained their original structure of wood, which burned with a brilliant light, and left a black dense charcoal.

The constituents of two specimens analysed by Dr. Kane, gave,—

	1.	2.
Volatile matter	57·70	53·70
Pure charcoal	33·66	30·09
Ashes	8·64	16·21
	100·00	100·00

From the above it would appear that the economic value of lignite is about two-thirds of an average quality of good coal; and comparing these with other results obtained from similar lignites, two-thirds may fairly be taken as the calorific value of this description of fuel. Dr. Kane further examined a great variety of turf, and amongst others those prepared by Mr. C. W. Williams from the bogs of Cappage, Kilbeggan, Kilbaken, &c.; the elementary products of which are, according to Dr. Kane, as follows:—

	Cappage.	Kilbeggan.	Kilbaken.
Carbon	51·05	61·04	51·13
Hydrogen	6·85	6·67	6·33
Oxygen	39·55	30·46	34·48
Ashes	2·55	1·83	8·06
	100·00	100·00	100·00

It will be unnecessary to exemplify a greater variety of fuels, such as the different kinds of wood used in America, Russia, and different parts of the continent. In this country timber is seldom, if ever, used; and taking the comparative merits of the fuels already enumerated, it will be found (in assuming the quantity of carbon contained in each as the measure of their respective values) that the Welsh furnace coal and the Newcastle and Lancashire coals stand pre-eminent in the order of their heating powers, either as regards their application to the furnace, or to the ordinary purposes of domestic life.

The American anthracites, which in some cases contain upwards of 90 per cent. of carbon, are extensively used in that country; and assuming the mean, 91·4, of Professor Johnston's experiments to be correct, and calling it at 1000, we then have an approximate value of the different fuels experimented upon and in general use in this country.

TABLE OF COMPARATIVE RESULTS, showing the calorific and economic Value of different kinds of Fuel.

No.	Quality.	Specific gravity.	Value.
	American anthracite coal	...	1000
1	Welsh anthracite coal	1·393	981
2	Welsh furnace coal........................	1·337	963
3	Newcastle coal	1·278	936
4	Lancashire coal	1·293	900
5	Welsh slaty coal...........................	1·409	898
6	Scotch caking coal........................	1·263	822
7	Scotch cherry coal	1·263	813
8	Scotch splint, 75·00; Scotch splint, 70·90 } Mean, 72·95 ...	1·278	799
9	Scotch cannel, 64·72; Scotch cannel, 72·22 } Mean, 68·47...	1·250	749
10	Derbyshire furnace coal..................	1·264	578

In this table the economic value is assumed to be in proportion to the quantity of carbon contained respectively in each sort of coal; and, provided the lignites and turfs are excepted, the others may safely be taken as nearly the correct value of the principal mineral fuels of the kingdom.

II. *The relative proportions of the furnace and the forms of boilers.*

On this part of the subject there are several points worthy of attention, namely, the proportions of the furnaces of stationary boilers of different constructions; the dimensions and position of those with exterior and interior fires; and the principle of form which approaches the nearest to a maximum calorific effect.

It is obvious that the hemispherical and waggon-shaped boilers are the best calculated to ensure abundance of space; and the furnace being detached and entirely clear of the boilers, a discretionary power is thus vested in every person choosing to experiment as to the length, breadth, or height of the hearth plate and bars which contain the fuel. Hence arise the anomalies which exist, and the innumerable theories which are advocated in every direction for improved furnaces and perfect combustion.

These discrepancies create great perplexities; and as much depends upon the management of the fire, and the will as well as skill of the engineer, it is next to impossible, from such a mass of conflicting evidence, to deduce anything like a correct proportional of the area of the grate-bar and the recipient surface of the boiler.

From a careful examination of some of the best constructed boilers and furnaces in Manchester, the following results were obtained:—

No. of Boilers.	Area of grate-bars in feet.	Recipient internal surface in feet.	Recipient external surface in feet.	Total heated surface in feet.	Ratio of grate-bars to heating surface.	Remarks.
6	36·0	195·0	......	......	......	In the first six boilers the external flues could not be measured.
1	30·5	167·2	175·0	342·2	1 : 11·2	
2	36·5	201·0	267·5	468·5	1 : 12·7	
2	28·3	154·8	180·5	353·3	1 : 12·0	
2	28·7	137·3	167·0	304·3	1 : 10·8	
2	40·6	150·4	207·3	357·7	1 : 8·9	
Mean	33·4	162·1	199·4	365·2	1 : 11·1	

The ratio of the grate-bar to the absorbing surface is therefore as 1 : 11·1, which, taken from fifteen different boilers of the best construction, and worked with considerable skill, gives a fair average of the proportions of the furnace and flue surface of each*. Now, on comparing the above with the boilers at work in Cornwall, it will be found that their relative proportions are as 1 to 25; the Cornish boilers presenting from two and a half, and in some instances three times the surface exposed to the action of the fire, in the ratio of the furnace to the flue as a recipient of heat. Taking the disparities as thus exhibited, it must appear evident that exceedingly defective proportions must somewhere exist, otherwise the anomalous comparison of a small fire and a large absorbent surface could not be maintained, unless the former practice of large fires and limited flue surface

* Considerable difference of opinion exists in regard to these proportions, some contending for a large absorbing surface, and others again asserting that under certain circumstances this is not wanted, particularly in marine boilers, where an active system of combustion is carried on.

had been found injurious and expensive. It is true that time is an element in every process of combustion, and that the system of quick and slow firing have each their merits and peculiar grounds of preference. To this may probably be referred one of the sources of economy, but economy in time and economy in fuel are two different things; each has its respective value. It nevertheless appears evident that a great waste of valuable fuel is the consequence of these defective proportions, and this is abundantly manifest from the results obtained in the quantity of water evaporated by a pound of coals in each case. For example, 1 lb. of good coal will evaporate in the Cornish boiler about 11½ lbs. of water; and the utmost that the best waggon-shaped boiler has been known to accomplish is 8·7 lbs. of water to the pound of coal. Hence the advantage of a small furnace and large flue surface, united, however, to abundance of boiler space, in order to attain a maximum effect by a slow and progressive rate of combustion. From the facts thus recorded, and the returns regularly made of the performances of the Cornish engines and boilers, it will no longer admit of doubt as to the superiority of the practice which exists in one country as compared with that in the other. Persons unacquainted with the subject have attributed the saving to the engine; but that doctrine, although in some degree correct, is no longer tenable, as experiments and the monthly returns unite in proving that part of the economy is due to the boiler; and the proportion of flue surface on the Cornish construction being so much greater, we reasonably infer that the recipient surface of the hemispherical and waggon boilers is insufficient, under a system of slow combustion, for the amount of fire-bar surface acting upon it.

These observations have in a great measure been corroborated by the introduction into the Lancashire districts of the cylindrical form, with a large circular flue, extending the whole length of the boiler. In this flue the furnace is placed, and being confined within certain limits it no longer admits of disproportionate enlargement, but, from the very nature of its

construction, forces old plans and old prejudices to yield to positive improvement.

The effect of the change is a progressive and improved economy in the consumption of coal, with a larger extent of flue surface, and, what is probably of equal value, a stronger and much more perfect boiler.

Irrespective of the changes of form and management of boilers which are in progress, it may be proper to notice a still further improvement in construction which has recently taken place, and where a still greater economy is effected. This is a mean between the Cornish single flue boiler and the tubular boiler; it is perfectly cylindrical, and contains two circular flues, varying from 2 feet 6 inches to 2 feet 9 inches in diameter, extending throughout its whole length, as represented and explained in another place in drawings which are annexed. Towards the front end the flues are made slightly elliptical*, in order to receive the furnace grate-bars, hearth-plates, &c., to give sufficient space over the fire, and to admit a free current of air under the ash-pit. On this plan it will be observed that each furnace is surrounded by water in every direction, with large intermediate spaces to allow a free circulation of the water, as the globules of heat rise from the radiant surface over the fires and the other intensely heated parts of the flues. Another advantage is the position of the receptacle for the sedimentary deposits, which do not take place over the furnace, as in the old construction, but in the lower region of the boiler, where the temperature is lowest; thus affording greater security from incrustation and other causes of an injurious tendency.

On the evaporative powers of boilers, it has already been shown that the process, to be conducted with economy, depends upon one of two causes, or both; first, on the due and perfect proportions of the furnace; secondly, which is more probable, on the quantity of flue surface exposed to the action of heat. No doubt they are both important agents in the procuration

* The elliptical form has for some years been dispensed with, and the circular form adopted on account of its superior strength.

and generation of steam, but the recipient surface is so important, that the measure of all boilers, as to their economy and efficiency, in a great degree depends upon the enlargement of those important parts. Taking, therefore, the amount of the flue surface in a boiler exposed to the passing currents of heat as a criterion of its economic value, we shall then have, according to computation, a summary of comparison as follows:—

No	Description of Boiler.	Cubic contents in feet.	Area of heated surface in feet.	Ratio of the area of heating surface to cubic contents.
1	Old hemispherical boiler	420	128	1 : 3·28
2	Common waggon boiler, without middle flue...	1044	320	1 : 3·26
3	Waggon boiler, with middle flue..................	894	432	1 : 2·06
4	Cylindrical boiler, without middle flue	789	225	1 : 3·50
5	Cylindrical boiler, with middle flue...............	579	360	1 : 1·65
6	Cylindrical boiler, with eight ten-inch iron tubes	605	567	1 : 1·06
7	Improved boiler, with two middle flues	573	548	1 : 1·01

On a comparison of the above Table, it will be seen that the generative powers of a boiler do not depend upon its cubic contents, nor yet upon the quantity of water it contains, but upon the area of flue surface exposed to the action of heat; and that the nearer the area of the flue surface approaches the cubic contents, the greater the economy and more perfect the boiler.

This has been proved by experiment, and also by practice in the use of Nos. 6 and 7 boilers, where the generative powers have been much increased, and where they approach nearer to the maximum than any other, excepting, probably, those with a number of small tubes, such as the locomotive, and the present construction of marine boilers*. These latter are, however, not so well adapted for stationary purposes, nor yet are they calculated for the attainment of other objects contemplated in this report.

* Mr. C. Wye Williams, in his excellent 'Treatise on Combustion,' maintains a different opinion. He says, "that the present construction of marine tubular boilers is the greatest violation of all chemical, physical, and economic laws as regards either combustion or vaporization that can be exhibited."

It has already been stated that the relative areas of fire-grate and flue surface, taken from a series of observations, are as 1 to 11*, and in the average of Cornish boilers as 1 to 25. Now, if we take the mean of these two, and fix the ratio at 1 to 18, we shall have a near approximation to a maximum effect; and, for general practice, it will be found that such a proportion will better serve the interests of the public, and of parties employing steam-boilers, than the extreme of 1 to 25 or 1 to 30, where a great increase of boiler power must be the result. In many situations, such as the large manufacturing towns, this cannot be accomplished, and to enforce such a regulation by legislative or municipal enactments, would be, to say the least, inexpedient and oppressive. Taking, therefore, the experiments, observations, and other circumstances bearing upon these points, into consideration, it will appear that the circular boiler, with an enlarged and extended flue surface, and accurately proportioned furnaces of about 1 to 18, is the best calculated under all circumstances for effecting the economy of fuel, and those other objects which have yet to be considered in the absence of smoke.

III. *The temperature of the furnace and the surrounding flues.*

It is a difficulty of no ordinary description to ascertain with sufficient accuracy the temperature of a furnace. In fact, every fire and every furnace is continually changing its temperature, as well as the nature of the volatile products, as they pass off during the process of combustion. When a furnace is charged with a fresh supply of fuel, its temperature is lowered, and that from two causes: first, by the absorption of heat which the coal fuel takes up when thrown upon the fire; and, secondly, by a rush of cold air through the open door of the furnace. Attempts have been made to remedy these evils by the aid of machinery and continuous firing; but taking the whole of the existing schemes into account, and bestowing upon them the most

* Since the above was written, I have received from my friend, Mr. Andrew Murray, of the Royal Dockyard, Woolwich, a series of experimental researches, some of which will be found at the close of the report.

favourable consideration, it is questionable whether they are at all equal (either as regards efficiency or economy) to the usual way of working the fires by hand. I am persuaded the latter plan is the best; and, provided a class of careful men were trained to certain fixed and determined regulations, and paid, not in the ratio of the quantity of coals shovelled on the fire, but in proportion to the saving effected, we should not then have occasion for the aid of machinery as an apology for inattention and ignorance.

Operations of this kind require but a small portion of physical strength in supplying a furnace with fuel (which a machine can do), but some measure of intelligence is necessary to watch over and assist nature in the development of those laws which determine as well as govern the process of combustion.

Viewing the subject in this light, it will not be uninteresting if we attempt to exhibit some of the important and exceedingly curious changes which take place in the ordinary process of heating a steam-engine boiler.

For these experiments we are indebted to Mr. Henry Houldsworth, of Manchester; and having been present at several of the experiments, I can vouch for the accuracy with which they were conducted, and for the very satisfactory and important results deduced therefrom.

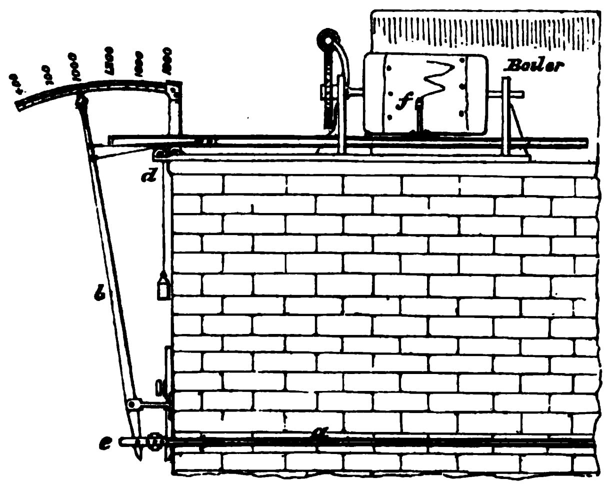
In giving an account of Mr. Houldsworth's experiments, it will be necessary to describe the instrument by which they were attained, and also to show the methods adopted for indicating the temperature, and the changes which take place in the surrounding flues.

The apparatus consists of a simple pyrometer, with a small bar of copper or iron (*a* in the following sketch) fixed at the extreme end of the boiler, and projecting through the brick-work in front, where it is jointed to the arm of an index lever *b*, to which it gives motion when it expands or contracts by the heat of the flue.

The instrument being thus prepared, and the bar supported by iron pegs driven into the side walls of the flue, the lever (which is kept tight upon the bar at the point *e* by means of a

small weight over the pulley at *d*) is attached, and motion

PYROMETER.



ensues. The long arm of the lever at *d* gives motion to the sliding rod and pencil *f*, and by thus pressing on the periphery of a slowly revolving cylinder, a line is inscribed corresponding with the measurements of the long arm of the lever, and indicating the variable degrees of temperature by the expansion and contraction of the bar. Upon the cylinder is fixed a sheet of paper, on which a daily record of the temperature becomes inscribed, and on which are exhibited the change as well as the intensity of heat in the flues at every moment of time. In using this instrument it has been usual to fix it at the medium temperature of 1000°, which, it will be observed, is an assumed degree of the intensity of heat, but a sufficiently near approximation to the actual temperature for the purpose of ascertaining the variations which take place in all the different stages of combustion consequent upon the acts of charging, stirring, and raking the fires. These are exemplified by Plates V. and VII. corresponding with Experiments No. I. and No. II.

On a careful examination of the diagrams, it will be found that the first (Exp. No. I.) was traced without any admixture of

air, except that taken through the grate-bars; the other (Exp. No. II.) was inscribed with an opening for the admission of air through a diffusing plate behind the bridge, as recommended by Mr. C. W. Williams. The latter, No. II., presents very different figures; the maximum and minimum points of temperature being much wider apart in the one than the other, as also in the fluctuations which indicate a much higher temperature, reaching as high as 1400°, and seldom descending lower than 1000°, giving the mean of 1160°.

Now, on comparing No. II. experiment with No. I., where no air is admitted, it will be found that the whole of the tracings exhibit a descending temperature, seldom rising above 1100° and often descending below 900°, the mean of which is 975°. This depression indicates a defective state in the process; and although a greater quantity of coal was consumed (2000 lbs. in 396 minutes in the No. II. experiment, and 1840 lbs. in 406 minutes in No. I.), yet the disparity is too great when the difference of temperature and loss of heat are taken into consideration. As a further proof of the imperfections of No. I. construction, it is only necessary to compare the quantities of water evaporated in each in order to ascertain the difference, where in No. I. experiment 5·05 lbs. of water were evaporated to the pound of coal, and in No. II. one-half more, or 7·7 lbs., showing the increase by a more perfect combustion.

Taking the results thus indicated, it will appear evident that the admission of a certain quantity of atmospheric air behind the bridge operates most advantageously, inasmuch as it combines with its constituents in due proportions, and by these means the gases are inflamed under circumstances favourable to the extraction of heat and the absence of smoke. The whole process is therefore distinguishable by the fact of one construction presenting a decreasing temperature when air is not admitted, and the other an increasing column when it is introduced. If no air is admitted, except through the grate-bars, and there happens to be a compact charge in the furnace, the consequence is that the gases pass through the flues unconsumed, and

accompanied with a dark volume of smoke, which is invariably present on such occasions.

It will not be necessary in this instance further to increase the number of diagrams, as No. I., which exhibits the variations and results of the intensity of heat when air is not admitted, and No. II. (with an aperture of forty-five square inches constantly open) will be found encouraging features for its admission in duly regulated proportions. These two diagrams will therefore sufficiently explain the varied changes of temperature which exist, and as all the other thirty are (with occasional deviations) nearly alike, the following Table of Results will probably answer the same purpose as if given in detail:—

Table of Results, selected from thirty experiments obtained by Mr. Houldsworth's Pyrometer, indicating the mean temperature of the flues in a steam-engine boiler, and the effects produced by the admission of air through regulated and permanent apparatus behind the bridge.

No. of Experiments as marked on the diagrams.	Description of coal used.	Aperture for the admission of air in square inches.	Coals burnt per hour.	Water evaporated by 1 lb. of coal in lbs.	Mean temperature in the front flue.	Relative value in the ratio of water evaporated.
12 13 and 28	Clifton } mean Oldham }	No air	243·00	6·21	°977	100 : 000
9, 10, 11	Clifton	......	278·40	5·41	973	100 : 87·1
7 and 8	Clifton	45	280·8	6·85	1·165	100 : 110·3
15 to 22	Clifton	{ Regulated by hand }	265·8	6·94	1·122	100 : 110·7
14	Clifton	45	279·0	6·60	1·220	100 : 106·2
30	Clifton	Regulated	279·0	6·80	1·160	100 : 109·5
24	Oldham	35	243·0	6·85	1·080	100 : 110·3
26	Oldham	24	229·2	7·40	1·050	100 : 119·1
23	Oldham	Regulated	230·4	7·70	1·070	100 : 124·0
25 to 29	Oldham	Regulated	216·6	8·30	1·053	100 : 133·6
27	{ Mixed, half of each sort. }	......	243·0	7·20	1·060	100 : 115·7

By comparing the results as given above, it will be found, that in taking the quantity of water evaporated by 1 lb. of coal as the measure of economic value, the mean of nearly the whole experiments (excepting only Nos. 12, 13, and 28, where air is not admitted) is as 100 to 112·65, or about 12½ per cent.

in favour of a regulated and continuous supply of air. Taking, however, the mean of experiments, 25 to 29, and comparing it with some of the others, it will be observed that a much higher duty is obtained; and having accomplished a maximum, there appears no reason for doubting why it should not be continued, and still further advantages secured by a judicious arrangement of the furnace for the admission of oxygen to the uninflamed gases, which under other circumstances would make their escape into the atmosphere unconsumed. In furnishing this supply, it is not absolutely necessary to administer it immediately behind the bridge, as the same quantity of air taken through the grate-bars, or in at the furnace-doors, would nearly effect the same purpose, not only as regards the quantity of heat evolved, but also as respects the transparency of the gases and the consequent disappearance of smoke*.

Mr. Houldsworth estimates the advantages gained by the admission of air (when properly regulated) at 35 per cent., and when passed through a fixed aperture of 43 square inches, at 34 per cent. This is a near approximation to the mean of five experiments, which, according to the preceding table, gives 33⅓ per cent., which probably approaches as near the maximum as can be expected under all the changes and vicissitudes which take place in general practice.

On a cursory view of the subject, it is obvious that the quantity of air necessary to be admitted will greatly depend upon the nature and quality of the fuel used. In a light burning fuel, such as splint and cannel coal, less air will be required, as the charge burns freely with clear spaces between the grate-bars, and is attended by less risk of cementation than the caking coal, which in some cases completely seals the openings, and thus deprives the fuel of that quantity of air necessary for its combustion. Under such circumstances, a permanent opening will be found exceedingly efficacious, and that

* On this subject see Mr. C. W. Williams's work, or that part of it which refers to the admission, diffusion, and mechanical admixture of air to the furnace.

more particularly when the heat vitrifies the earthy particles of the coal, and forms clinkers on the top of the grate-bars. In the use of this description of fuel the permanent apertures are of great value.

The constituents of coal vary in quality as well as degree, and this may be seen from what has already been stated in the analyses given by recognized chemical authorities at the commencement of the inquiry. In order, therefore, to provide for these differences, and to effect its perfect and economical combustion, it will be necessary to show in what manner and under what circumstances its gaseous products combine with other elements essential to produce the phænomenon which we call flame, or the combustion of fuel. When all the elementary substances are present, two things appear to be necessary to effect combustion, and these are heat and the requisite quantity of oxygen as its supporter. Now this latter element is supplied in great abundance from the atmosphere; but as it is mixed with another gas, nitrogen, from which it has to be separated before it unites with the hydrogen and carbon of the fuel, it becomes absolutely necessary to maintain, not only a high temperature in the furnace, but to afford facilities for the requisite supply of air under all the varied conditions of slow to active combustion. As the evolving gases will combine with no more than their correct equivalents of oxygen, it becomes a question of great importance to approximate as nearly to the right quantity as possible, and to admit neither more nor less air than is necessary to furnish these equivalents. If more air is admitted than what is required, the temperature is reduced; and on the other hand, if too little air is admitted, an imperfect combustion ensues, and the usual defects of a turbid black smoke is the result. When the proper quantity of atmospheric air is supplied, and a sufficiently high temperature of the furnace is maintained, a perfect process of combustion is then effected: the carbon of the coal, under these circumstances, is converted into carbonic acid, whilst that of the hydrogen is converted into water in the shape of vapour.

In this state of the furnace the products of combustion become invisible, and hence we may reasonably conclude that smoke, whenever or wherever it is presented, is neither more nor less than the result of imperfect combustion. A high temperature being therefore one of the conditions necessary to effect combustion, it is of great importance that we should know at all times the varied forms and temperatures at which the gases pass from the furnace into the flues and the chimney; and also, that we should register the indications of temperature on the principle which is so neatly and so ingeniously illustrated by Mr. Houldsworth's pyrometer. These indications are of great value, as they lead to the maintenance of a sufficiently high temperature to ensure a perfect combination of the chemical compounds, and at the same time to pass off the vaporous products of the furnace in their transparent and indivisible forms*.

Sir Humphry Davy, in his experiments on flame, has proved all those facts; and he has further proved, that in the chemical combination of air and gas, a high temperature is required. In some of those researches he found that air and gas could not be inflamed with red-hot iron, and that it required the gaseous mixture to be raised to a white heat before ignition or explosion ensued. Mr. C. W. Williams also maintains this opinion; and in speaking of Davy's experiments, he states, "That this heat" —meaning the temperature at which the gases combine—"is

* In this investigation I have not touched upon the question that bears upon the nature and quality of the products of combustion as they issue from steam-engine chimneys or common fires; nor yet have I inquired whether they have or they have not—under certain conditions of an improved process—undergone a chemical change, either as respects their deleterious character when discharged from the funnels or chimneys in a transparent or indivisible form, or under any other condition arising from defective combustion. That is a subject still open for inquiry, and although it is not entirely distinct from that now under consideration, it is nevertheless not immediately connected with it. Suffice it, therefore, to observe, that the removal of the black carbonaceous matter which now darkens the atmosphere is an important point gained, and that alone is a step in advance, independently of other conditions under which the residuum of combustion may make its escape.

required for the ignition of the *first mixed group of gas and air* to which it is applied, we have daily proof, when, to light the gas in our apartments, we apply the heat of a *separate flame* before ignition takes place."

"This is confirmatory of the high temperature described by Sir H. Davy, since, as he observes, 'the temperature *of white hot metal is far below that of flame.*' Now in lighting the gas from our burners, we are apt to overlook the all-important fact, that it is not the gas which we ignite, but *the mixture of gas and air.*

"On the taper being applied, explosion or sudden ignition then takes place of *just so much, or so many groups of the gas and air as have obtained the necessary atomic contact, and no more.*

"That a high temperature must, unintermittingly, be maintained in the chamber part of the furnace, will at once be understood, when we consider that flame, continuous though it appears to be, is but a rapid succession of electric explosions of atoms, or groups of atoms, of one of the constituents of gas—the hydrogen with oxygen; and as rapidly as their respective atoms obtain access and contact with each other, the second constituent—the carbon—taking no part in such explosions. Whatever, therefore, interrupts this succession (that is, allows the explosion of one group to be terminated before another is ready, and within the range of its required temperature), virtually causes the flame to cease; in ordinary language, puts it out.

"Again, if by any cooling agency we reduce the temperature below that of accension, or kindling, the effect is the same: *the succession is broken,* and the continuousness of the flame ceases; as when we blow strongly on the flame of a candle, by which we so cool down the atoms of gas that they become *too cold for ignition,* and pass away in a grey-coloured vapour, but which, by contact with a lighted taper, may again be ignited and the succession restored.

"Thus we see there are two modes by which flame may be intercepted, that is, extinguished; both of which are momentarily in operation in our furnaces:—1st, by the want of successive mixture or groupings of air and gas; 2nd, when the

gas is reduced in temperature by cooling agencies, as will hereafter be shown."

From these extracts, and taking into account the carefully conducted experiments of Sir Humphry Davy, there cannot exist a doubt as to the necessity which exists for preventing a surcharge of cold air acting upon the furnace. Its high temperature is essential to its efficiency, either as regards economy in the use of the fuel, or the equivalents of ignition with atmospheric air.

The question of temperature applied to combustion is therefore one of great interest. It involves many considerations, both mechanical and chemical, and although apparently of easy attainment, it is nevertheless surrounded with many difficulties. Our knowledge of high temperatures, as well as our instruments for measuring their intensities, are far from perfect; and we have yet to learn at what temperature the gases unite, or, as Mr. Williams calls it, ignite "in a series of electric explosions" with atmospheric air. This temperature, or rather the lowest temperature at which the gases and atmospheric air will unite, has not yet been ascertained: some fix it at 800°, and some others at 1000° of Fahrenheit. These degrees of temperature are, however, highly problematical, as Sir H. Davy's experiments seem to prove that a white heat is necessary to produce the phænomena of combustion; and as atmospheric air seldom exceeds 80° to 90° of temperature, it is evident, that when air of this temperature is poured upon the incandescent fuel, it will rob the evolving gases of a portion of the heat essential to combination, and thus reduce the temperature in many cases below the point of ignition.

The combustion of fuel is to all appearance an easy as well as a natural process; but on mature consideration it will be found that before we can arrive at sound practice, we must have some knowledge of science; and before we can make a single step in advance, it must be done through those laws which the Great Author of Nature has so bountifully and so invitingly supplied for our guidance.

LECTURE IV.

ON THE ECONOMY OF FUEL, CONCENTRATION OF HEAT, AND PREVENTION OF SMOKE.

IRRESPECTIVELY of the intensity of heat, form of boilers, and quality of fuel, as described in the last Lecture, there are other conditions connected with the phænomena of combustion which require attentive consideration before that process can be called perfect, or before economy or the prevention of smoke can be attained. It is perfectly clear, that although we may possess abundance of excellent fuel, and a perfect knowledge of all the elements necessary for its combustion, yet we are still far short of attaining our object, unless a due regard to economy is strictly kept in view. A manufacturer may have well-proportioned boilers, excellent furnaces, and good fuel, but with all these advantages he will not succeed, unless the whole of the elements at his command are properly and economically combined, and that upon fixed laws already determined for his guidance. Count Rumford, in his admirable 'Essays on the Economy of Heat,' truly observes, that "No subject of philosophical inquiry within the limits of human investigation is more calculated to excite admiration and to awaken curiosity than fire, and there is certainly none more extensively useful to mankind. It is owing, no doubt, to our being acquainted with it from our infancy that we are not more struck with its appearance, and more sensible of the benefits we derive from it. Almost every comfort and convenience which man by his ingenuity procures for himself is obtained by its assistance, and he is not more

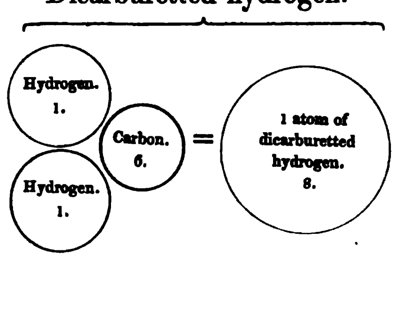
distinguished from the brute creation by the use of speech, than by his power over that wonderful agent."

Such was the opinion of one of the most eminent philosophers of his time, and such were the pertinency of his remarks and the depth of his researches, that had he lived in the present instead of the close of the last century, he would not only have extended and enlarged our views on the management and economy of heat, but he would have expressed astonishment at the increase, the immense extent of expenditure, and the lavish and culpable waste of fuel by which we are surrounded on every side. It is true we have some exceptions to this rule, such as the engine boilers in Cornwall and some parts of the continent, where fuel is expensive; but taking the aggregate, it might be said, without fear of contradiction, that if one-half of the fuel now used were properly applied, it would perform the same service, and afford the same comforts, as we now derive from the whole consumption of our mineral products. This is a great reflection upon the philosophy as well as the economy of the age, and I think it can be shown that one-half the fuel now wasted might be saved with great advantage to individuals, and with increased benefit as well as comfort to the public. The wasteful expenditure which exists does not arise so much from ignorance as from prejudice, and a close adherence to old and imperfect customs. We all, more or less, venerate the works of antiquity, but unfortunately we forget to draw the distinction between what is really ancient and sound in principle, and what is imperfect in practice. Hence follows a blind adherence to established usage, and the consequent propagation of all the defects as well as the perfections of the system. Now this state of things should not exist, as we have the experiments of Watt, Rumford, Davy, Parkes, and many others before us; and adding to these the excellent treatise of Mr. C. W. Williams on the combustion of coal and prevention of smoke, we are enabled by these means to establish a sound and much more perfect as well as economical system of combustion. Keeping these objects in view, we shall endeavour to determine some fixed principle on which

may be founded the prevention of smoke, concentration of heat, and economy of fuel.

It is well known that in practical operations there is no combustion without oxygen as its supporter; and as that important element cannot be procured for general purposes without the other constituents of atmospheric air, it follows, that in order to effect combustion, a regular supply of this compound must be constantly at command. Now it is not the facility, but the control and regulation, of the supply of air which requires attention, and on this point of the inquiry we must refer to the researches of Mr. C. W. Williams, where, in speaking of "gaseous combinations," he shows that much depends upon the conditions and proportions in which the gases evolved during the process of combustion combine with the oxygen of the air. And in order to effect this, it is necessary for those entrusted with the management of furnaces to know the "equivalents" or definite proportions under which these combinations take place. On this head it will be sufficient to observe, that the principal gases evolved from coal in a state of combustion are light carburetted hydrogen, heavy carburetted hydrogen or olefiant gas, and some others, such as carbonic acid gas, carbonic oxide, &c., the properties of which it is not requisite on this occasion to investigate, but to confine the inquiry to the union of light carburetted hydrogen and heavy carburetted hydrogen with the oxygen of the atmospheric air. Following therefore the Daltonian theory, it will be found that the constituents of one atom of light carburetted hydrogen or dicarburetted hydrogen, consist of the following symbols, each representing an atom, and the figures the weight:—

Dicarburetted hydrogen.

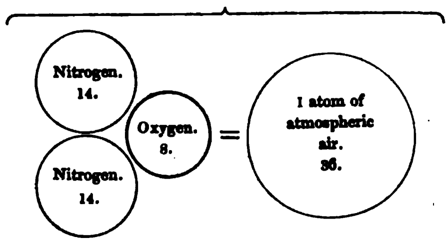


Dicarburetted hydrogen is therefore composed of 2 equiv. hydrogen and 1 equiv. carbon = 1 equiv. dicarburetted hydrogen. In weight 2 hydrogen + 6 carbon = 8 dicarburetted hydrogen. The constituents of heavy carburetted hydrogen are, 2 equiv. hydrogen and 2 equiv. carbon = 1 equiv. heavy carburetted hydrogen. In weight, 2 hydrogen and 12 carbon, or $2+12=14$ heavy carburetted hydrogen.

These are the two principal gases which require attention, and as the oxygen of the air is an element that cannot be dispensed with, the object of our next inquiry will be the quantity and constituents of atmospheric air.

According to the best authorities, atmospheric air is found in the proportion of 1 equiv. of oxygen to 2 equiv. of nitrogen, or, according to Mr. Williams (and adopting the figures as representing the weights as before):—

Atmospheric air.



Having thus ascertained the constituents and equivalents in which the combustible and incombustible gases combine, it will easily be determined what quantity of atmospheric air will be necessary to support and effect perfect combustion of the fuel of which the above are constituents. For this purpose it will be observed that a very considerable quantity of air must be brought in contact with the incandescent fuel, before the process of combustion can be effected; and having already determined the constituents of each, we must next determine the quantity of air required for the purpose of supporting the entire combustion of the gases, without producing a diminution of the temperature in the process.

Mr. T. Symes Prideaux, in a lecture recently delivered to the

Members of the United Service Institution, states, in allusion to coal and its constituents, that different kinds vary considerably in their component parts, and their relative proportions to each other. From these differences he assumes—as a convenient standard of illustration—that 100 parts of coal consist of 80 parts of carbon and 5 of hydrogen, leaving out of view the other elementary substances which enter into their composition (consisting of oxygen, nitrogen, sulphur and incombustible ashes, composed chiefly of sand and clay in various proportions) as only likely to complicate the question, without being essential to its illustration.

Mr. Prideaux assumes the proportion of 80 and 5 for the composition of coal, on account of its practical convenience, as it enables him to prove that—

"As hydrogen furnishes—weight for weight—four times as much heat as carbon, the 5 parts of hydrogen will furnish 20 per cent. of the whole heat, and the 80 parts of carbon 80 per cent., being the same proportionate part of the heat as it forms by weight of the fuel; 100 lbs. of coal consist then of 80 lbs. of carbon and 5 lbs. of hydrogen."

In these statements Mr. Prideaux goes on to state—

"That carbon may be said to be the grand material out of which the vegetable and animal worlds are formed; and hence," he observes, "its abundance in coal—the fossilized remains of the luxuriant vegetation of an earlier geological epoch.

"All vegetable and animal substances, if only partially burnt (that is to say, raised to a high temperature without a free supply of air), are convertible into charcoal; or, more correctly speaking, this is left as a residue after the more volatile constituents are driven off by heat, assuming various forms according to its previous state of aggregation; as common or *wood*-charcoal, coke or *coal*-charcoal, ivory black or *bone*-charcoal, tinder or *linen*-charcoal. The whole of the carbon these substances contain, is not, however, left behind after partial burning or dry distillation. The hydrogen present in them exists in a state of chemical combination with carbon, and when heated, this volatile substance passes off with the carbon with which it is combined in the gaseous form as carburetted hydrogen, a gas consisting of 1 part by weight of hydrogen to 3 of carbon.

"Thus as hydrogen, in carburetted hydrogen or coal-gas, is combined with three times its own weight of carbon, in a coal containing 5 lbs. of hydrogen and 80 lbs. of carbon in the 100 lbs., 15 lbs. of the carbon exist as carbu-

retted hydrogen, and pass off in the gaseous form upon the application of heat. This is, in fact, the coal-gas we use for illuminating purposes, of which 100 lbs. of such a coal would furnish 20 lbs., or about 470 cubic feet.

"Now, since weight for weight, hydrogen affords on combustion four times the quantity of heat that carbon does, this 20 lbs. of carburetted hydrogen, consisting as it does of ~~8~~ 5 lbs. of hydrogen and 15 lbs. of carbon, represents 35 per cent. of the heating power of the coal."

Mr. Prideaux, having discussed the relative properties and proportions of hydrogen and carbon in coal, then proceeds to observe, that, in order to attain a clear perception of the conditions necessary for the economic prevention of smoke, two important points are required, namely,—

"The admission of the right QUANTITY *of air in the first place, and the supply of an adequate amount of* HEAT *to ensure ignition in the second."*

This, according to the writer, is the true and correct method of obtaining from the fuel all the heat it is capable of yielding; or in other words, it entails the prevention of smoke,—

"Inasmuch as all smoke consists of a portion of the carbon of the fuel passing off unburnt."

To attain these objects, and to prevent the escape of the unconsumed carbon, Mr. Prideaux asks himself this question, viz. How can these two simple conditions—the right quantity of air and sufficient heat—be best practically attained, and thus perfect combustion and its concomitant absence of smoke be ensured? This, he maintains, is done by the admission of air through the furnace-door, varying the supply according to the wants of the furnace, or as Mr. Prideaux expresses it,—

"The demands of the furnace for air varies greatly with the state of gasification of the fuel, the quantity of air being greatest just after the period of coaling, and gradually lessening till gasification is complete."

Following the same reasoning as before, and assuming 100 lbs. of coal to consist of 80 lbs. of carbon and 5 lbs. of hydrogen, Mr. Prideaux goes on to state, that

"Since the oxygen is to the carbon in carbonic acid as 16 to 6, to effect perfect combustion, 80 lbs. of carbon will require 213⅓ lbs. = 2527 cubic feet of oxygen, to furnish which 967·26 lbs. = 12635 cubic feet of atmospheric air will be required; and since oxygen is to hydrogen in water as 8 to 1, 5 lbs.

of hydrogen will require 40 lbs.=473 cubic feet of oxygen, or 181·5 lbs.= 236·5 cubic feet of atmospheric air. Hence 967·26 lbs.+181·5=1148·76 lbs. =15,000 cubic feet of air, required for the combustion of 100 lbs. of coal."

The products of combustion according to this statement, therefore, will be 2527 cubic feet of carbonic acid, 946 cubic feet of steam, and 12,000 feet of uncombined nitrogen.

From the foregoing extracts, it will be seen that under the assumption that 100 lbs. of coal contains 80 lbs. of carbon and 5 lbs. of hydrogen, Mr. Prideaux does not differ widely from the chemical combinations given by Mr. C. W. Williams. The only question wherein they appear to differ, is the mode of introducing the air to the furnace, Mr. Prideaux recommending a variable or gradually diminishing supply of air through division-plates at the mouth of the furnace, and Mr. Williams contending for a uniform admission—by its subdivision into minute jets—on the principle of the Argand lamp; or, as Mr. Williams properly calls it, the Argand furnace. Both these methods have the desired effect in preventing smoke when the furnace is properly charged and judiciously managed.

On this part of the subject several other and able authorities may be quoted; but taking that of Professor Brande (as given by Mr. Williams), the following table indicates the relative weights of the atoms both before and after combustion :—

Before combustion. Weight.		Elementary mixtures. Atoms.	Weight.	Products of combustion. Weight.	
8	Carburetted Hydrogen.	1 Carbon	6	22	Carbonic acid.
		1 Hydrogen	1	9	Steam.
		1 Hydrogen	1	9	Steam.
144	Atmospheric Air.	1 Oxygen	8		
		1 Oxygen	8		
		1 Oxygen	8		
		1 Oxygen	8		
		8 Nitrogen	112	112	Uncombined nitrogen.
152			152	152	

Again, for the olefiant gas, or heavy carburetted hydrogen, we have,—

Before combustion. Weight.		Elementary mixtures. Atoms.	Weight.	Products of combustion. Weight.
14	Carburetted Hydrogen.	1 Carbon	6	22 Carbonic acid.
		1 Carbon	6	22 Carbonic acid.
		1 Hydrogen	1	9 Steam.
		1 Hydrogen	1	9 Steam.
216	Atmospheric Air.	1 Oxygen	8	
		1 Oxygen	8	
		1 Oxygen	8	
		1 Oxygen	8	
		1 Oxygen	8	
		1 Oxygen	8	
		12 Nitrogen............	168	168 Uncombined nitrogen.
230			230	230

From the above it appears obvious that in every instance of combustion the nitrogen or azotic gas (which forms so great a proportion of atmospheric air) is about four times the volume and three and a half times the weight of the oxygen, and being in itself incombustible, is absolutely of no use either as a combustible or as a supporter of combustion. On the contrary, it is exceedingly injurious, for whilst it does not combine with the other gases, it at the same time reduces the temperature of the flame, and thus deprives the fuel of a great portion of its heat, which otherwise would (as in the case of the Bude light) have given much greater intensity of heat, and greater brilliancy in its illuminating powers. Finding it, however, impossible to separate the nitrogen from the oxygen of the air (for general purposes), we must take the mixture as it is, and instead of using 1 atom of oxygen, we must take 2 of nitrogen along with it; and as 4 atoms of oxygen and 8 of nitrogen are required for the ignition of 1 atom of light carburetted hydrogen, it follows that ten times the quantity of air in volume, and eighteen times the weight, will be necessary for that purpose. Again, for the ignition of 1 atom of heavy carburetted hydrogen, we must have 6 atoms of oxygen and 12 of nitrogen, and the atmospheric air must be fifteen times the volume of the olefiant gas in order to have perfect combustion. Fifteen to one is therefore the true proportion of atmospheric air required for attaining the perfect

combustion of coal gas, and for reducing the gases to their ultimate products of carbonic acid and water*.

Having determined the conditions and relative proportions of the gases and their supporters in a state of perfect combustion, it will be seen that in order to ensure economy and effect in the combustion of fuel, a large and copious supply of air must be admitted to the furnace, and that in the ratio of 15 volumes of air to 1 of coal-gas. It is difficult to determine the exact quantities evolved from every description of fuel, and probably equally so to supply its equivalent of air; but in order to attain certainty in this respect, let the openings be made sufficiently large, and by a little attention to the quality of the fuel and quantity of air required for its combustion, the apertures may be contracted till such time as a mean average and a close approximation to the maximum effect are obtained.

The *Concentration of Heat* is a consideration of much importance in the economy of the steam-engine and the industrial arts; and as much depends upon the preservation of this heat, it may be useful in this place to direct attention to a few self-evident facts, which, if properly attended to, will lead to considerable saving in the use and application of heat.

It cannot be doubted that, after having applied the rules, conditions, and proportions requisite for the generation of heat, the whole of our knowledge may become obsolete unless the heat thus generated be closely preserved, and, if I may use the expression, *kept warm*. It would be worse than useless to study economy in one department, so long as a lavish expenditure goes on in another; and having once acquired a given quantity of heat, the next thing to be done is to retain and prevent its escape. Caloric is a body which radiates in all directions, and, unless surrounded with warm clothing or non-conducting substances, it is sure to disappear; and, although

* When flame is applied to a mixture of 1 vol. of olefiant gas and 15 vols. of atmospheric air, explosion takes place, the products being carbonic acids, water, and nitrogen: thus we have

$$1 \text{ vol. olefiant gas} + 15 \text{ vols. air} = C_2H_2 + O_6 + N_{12}.$$

tightly bottled up, it sets at defiance the closest and hardest metals, and frequently escapes through the pores of the thickest iron and steel. Unlike gases and fluids, such as air and water, it is only kept within bounds by an envelope of soft wool or pounded charcoal, and the highest temperature of heat may sometimes be retained by a solid compact mass of lime and baked clay. This is strongly exemplified in the construction of ovens and furnaces, which, taken as a rule, will establish the principle on which heat can be preserved without diminution till it is used. For this purpose we should recommend the flues and furnaces of boilers and other fires to be closely encased with good building material adapted for the retention of heat, and all steam-boilers to be well covered and clothed, so as to prevent (as much as possible) the escape of heat in that direction; and for steam-engines, that all the steam-pipes, cylinders, &c. should be closely enveloped in a thick coating of felt, canvas, or wood, and afterwards well painted. These precautions being taken, the effects will soon become visible in a saving of 15 to 20 per cent. of fuel.

On the Prevention of Smoke.

The ultimatum of this inquiry is twofold; first, the combustion of fuel; and secondly, the prevention of smoke. In the preceding investigation we have endeavoured to establish the laws which regulate and govern the combustion of fuel, and in that attempt we have also endeavoured to show the difference between perfect and imperfect combustion. Now, perfect combustion is the *prevention of smoke,* and whenever smoke makes its appearance, we may reasonably infer that there is imperfect combustion, and, probably, the want of attention to a few simple rules is the cause. We have already inculcated these rules, and shown from well-known chemical facts, that 1 atom of coal-gas requires 8 atoms of atmospheric air for its complete combustion; *when that quantity is at its maximum or in excess, there is no smoke*; *when this condition is not fulfilled, smoke is invariably present.* It therefore follows, that, in order to render the residue of the products of combustion transparent or "*smoke-*

less," a supply of air, amounting to fifteen times that of the gases evolved, must be admitted. Should it exceed that quantity, the effect will not be smoke, but an additional expenditure of fuel to supply the loss of heat which this excess of air would require for absorption, rarefaction, &c. Hence the necessity which exists for power to regulate the admission, if not the exact, at least of an approximate quantity of air. On the other hand, should the supply be deficient in quantity (which is often the case), a dense volume of smoke is then visible, accompanied with all the defects and annoyances of imperfect combustion.

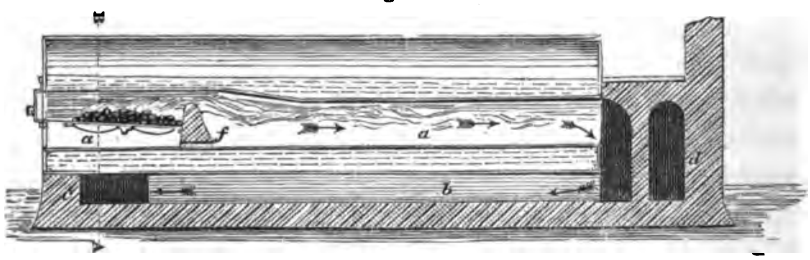
The variable changes which accompany perfect and imperfect combustion are not only visible, but may be proved by experiment. Let any person apply his hand to the tube of an Argand gas-burner, and he will find that the instant the aperture is partially closed, the flame immediately becomes elongated, and instead of a clear brilliant light, a dull red flame, with a dark volume of smoke, is the result. This shows the effect of a diminished supply of air; and the same may be applied to a steam-engine furnace, when imperfectly supplied with oxygen, when the gases pass off in opake volumes unconsumed, and where a considerable portion of heat is entirely lost from that cause. It has been stated that we cannot have fire without smoke; but this is not the case in steam-boilers, as a well-constructed furnace, properly managed, furnishes many examples where bituminous coal is consumed in large quantities, and with little, if any, appearance of smoke. If coal were double the price, it is more than probable that a great improvement would shortly present itself, and that not exclusively in the suppression of the smoke nuisance, but in a further extension of those duties wherein economy becomes a leading feature in the attainment of these objects. It is therefore futile to urge difficulties which have already been overcome, and where, in many instances, "the prevention of smoke" is accomplished with perfect ease, and with great benefit to the parties concerned. In attempting the total suppression of this nuisance, two important considerations require to be attended to as

essential; the first of which is *abundance of boiler space,* and the second a *sufficient supply of air.* For the last of these we have already given sufficient instructions for its admission; and for the first we could not furnish a better rule for the capacity and power of boilers than that which applies to the steam-engine, namely, that of raising 33,000 lbs. 1 foot high in a minute. For example, suppose a steam engine of 50-horse nominal power to be worked according to the indicator up to 80-horse, which, taken at 33,000 lbs. 1 foot high in a minute, we have then to calculate, from data already given, the size of boilers required. Using these precautions, and never loading the steam-engine beyond its nominal power without enlarging the boilers in proportion, the effects will be an almost total suppression of smoke, and a saving of fuel.

To all those practically acquainted with the subject, it is well

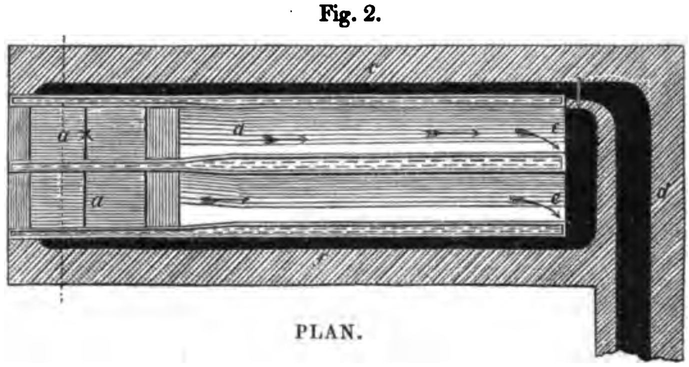
IMPROVED STATIONARY BOILER.

Fig. 1.



SECTIONAL ELEVATION.

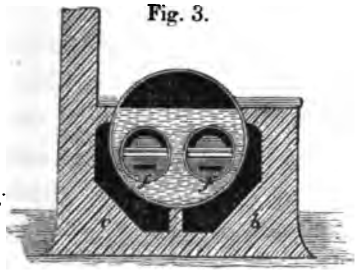
Fig. 2.



PLAN.

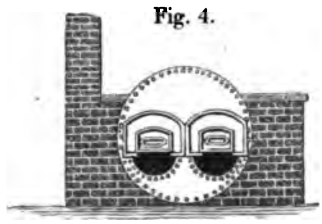
known that a boiler of limited capacity, when overworked, *must be forced, and this forcing is the gangrene which corrupts and festers the whole system of operations.* Under such circumstances perfect combustion is out of the question, and any attempt at economy is, as heretofore, a complete failure. I

Fig. 3.



SECTION AT A B.

Fig. 4.



FRONT OF BOILER.

have been the more particular on these points from having witnessed innumerable errors and mistakes in this respect, and it cannot be too forcibly impressed upon the minds of the public, that a LARGE BOILER is one of the essentials absolutely necessary for the attainment of the various objects already insisted upon.

Description.—Figs. 1 and 2 represent a plan and longitudinal section of the boiler, with double flues and double furnaces, and figs. 3 and 4 a transverse section and end view. In these representations it will be seen that the gases emitted from the furnaces *a*, *a*×, are conducted along the internal tubes into the return flue *b*. From *b* they cross under the boiler below the ash-pit into the flue *c*, and from thence along the opposite side of the boiler into the main flue *d*, which communicates with the chimney. From this description it will be observed that the gases do not unite until they have reached *e é* at the end of the boiler. At this point a change immediately takes place in the gaseous products, and that from one of two causes, as follows: suppose the furnace *a*× to be newly fired, and the fuel in it in a perfectly incandescent state, it then follows that the gases passing from *a* will not only be different in their constituents to those from *a*×, but they are at a much higher temperature; and both furnaces having received air as a

constant quantity through the fixed apertures *f f*, it will be seen that, in the event of a surcharge of air on one side and a diminished supply on the other, their extremes are neutralized by the excess of oxygen thus introduced, and the increased temperature which effects ignition in the furnace as well as at the point *e*, where combination takes place. All that is therefore necessary is to replenish the fires alternately every twenty minutes, in order to effect the combustion of the gases without the least appearance of smoke. These, and the increased recipient surface, are the leading properties of this boiler, which, compared with others having single flues, is found to be greatly superior either as regards the combustion or the economy of fuel.

General summary of results.

In briefly recapitulating the experiments, observations, and results obtained, it will be seen that in the procurement and employment of heat, a number of important matters have to be considered.

1st. The quality and properties of the fuel used.

2nd. Its treatment in the furnace, and the supply of air requisite for its combustion.

3rd. The form of boilers, and the extent of their absorbent surfaces.

4th. The concentration and economy of heat. And

Lastly. The prevention of smoke.

These have been treated upon in their respective order, and all that now remains is to collect them into form, and draw such conclusions as will enable practical men to understand and apply the means necessary for their fulfilment.

From what has been stated, and from the many facts collected and experiments made, it will appear conclusive that a much better and more comprehensive system of combustion can be accomplished; and by attention to the following results, great and important advantages may be obtained.

Among the varied species of fuel enumerated in the foregoing experiments, there will be found ten different sorts of coal, each exhibiting its peculiar properties and compounds.

For the sake of brevity and deduction, these may be divided into three kinds, namely, the anthracite, the bituminous, and the splint. Of the anthracite we have little experience beyond a knowledge of its most striking properties, such as the absence of smoke during its ignition. It is a coal which requires a large supply of oxygen for its combustion, and instead of the furnace usually employed for the consumption of the bituminous kind, it would require one possessing the power of a reverberatory or a strong blast acting upon it, and that under circumstances of a minute division of its parts.

The bituminous kind is, however, what we have most to do with; and on reference to its constituents, it will be seen that a specific quantity of atmospheric air is absolutely necessary for its combustion, amounting, as already stated, to fifteen times the volume of gases it contains. Now, from a number of well-conducted experiments on the waggon-shaped, and the improved boilers with double flues, it was ascertained that the following proportions of permanent openings for the admission of air behind the fire-bridge were the nearest approach to perfect combustion*.

Summary of Results, obtained from seventeen experiments with fixed apertures for the admission of air behind the bridge of two 40-horse power boilers.

Description of Boilers and number of Experiments made.	Power of Boilers in horses.	Area of grate-bars in feet.	Area of permanent aperture in square inches.	Number of square inches of aperture to every foot of grate-bar.
Waggon-boiler, mean of 10 experiments	40	28·0	46·3	1·65
Double furnace-boiler, mean of 7 experiments	40	23·4	18·5	·79
Mean	40	25·7	32·4	1·26

* It is due to Mr. John Wakefield (formerly of Manchester, now of Farnworth, near Bolton) to state, that he was amongst the first who turned his attention to the admission of air at the bridge, behind the furnace, for the purpose of consuming the smoke as it escaped into the flues. His first furnace was constructed on a plan of his own, having a hollow bridge closed at the top, and thus rendering it an air-chamber connected with openings on

It therefore appears that about 26 square feet, and $32\frac{1}{2}$ inches of permanent aperture for the admission of air, is the mean of the old and improved boilers.

This proportion must not, however, be taken as a criterion for every boiler, as much depends upon the principle on which they are constructed; and it will be safer to adopt the mean results of the experiments as shown in the table, than to apply them without exception to every description of boiler and furnace. Taking, therefore, the mean of the whole experiments, we may safely administer the following supply of air behind the bridge.

For cylindrical, waggon-shaped, and every description of boiler of the usual construction, give permanent opening for the admission of air of $1\frac{1}{4}$ square inch to every square foot of grate-bar; and for every square foot of grate-bar surface in the double-furnace and double-flued boiler, about an inch for the same purpose*.

Practically considered, this will be found a near approximation to the correct quantity of air required for the support of effective combustion in each; and provided necessary attention is paid to considerations involving the consumption of bituminous coal, of different kinds, we may reasonably infer a greatly improved process in the use and absorption of our mineral fuels.

In the combustion of splint and slaty coal, a different treat-

each side of the urnace. On this plan the air was heated by the passing currents, and by a communication from the air-chamber to an opening in the arch plate over the furnace door; the air thus rarefied was forced downwards, by the form of the opening in the plate, direct upon the fire. A variety of other schemes were tried by Mr. Wakefield, some of them successfully; and it is only justice to that gentleman to state, that a considerable portion of his life was devoted to improvements in steam-boiler furnaces, and the abatement of a nuisance which at that period (nearly thirty years ago) was justly complained of.

* Mr. C. W. Williams maintains that 4 to 6 square inches is not too much for the admission of air behind the bridge; but in these experiments a certain proportion was passing through the furnace doors independently of the supply by the usual channel between the grate-bars.

ment will be required as respects either the anthracite or the bituminous kinds; the one is obdurate and hard, the other is compact, and in some instances liquefies like pitch. Now the splint and slaty specimens burn openly and rapidly, and therefore require less air, exclusively of what is taken through the grate-bars.

In some cases it may, however, be necessary to overtake and effect the ignition of such gases as may escape over the bridge unconsumed, and for this purpose, in some descriptions of light coal, it may be desirable to admit about half the quantity of air used in the combustion of the bituminous kinds.

The ultimate results are, therefore,—

A perfect knowledge of the properties of the fuel used, and judicious management in working the fires.

An increase in the area of recipient surface of the boiler in the ratio of the furnace as 1 to 18; or what is the same thing, a reduction of the grate-bar surface to that proportion.

A constant supply of air (through a fixed aperture) of $1\frac{1}{4}$ square inch to every foot of grate-bar in common boilers, when burning bituminous coal; and about an inch area when using splint coal. These openings should, however, be regulated in the first instance by hand, until the mean or maximum effect in reference to the fuel is obtained.

A complete covering of felt, or some other non-conducting substance, to be applied to the exterior parts of the boiler, and the flues to be well protected on all sides from the external air.

On a strict observance of these rules will depend the question of *smoke* or *no smoke*, and also whether an important economy in the use of fuel shall or shall not be effected. We are assured, from the experimental facts already recorded, that both these objects can be accomplished, and it rests with the community to determine how far they shall be carried into effect.

At the time of entering upon this investigation, it was my intention to have confined it within exceedingly narrow limits: it was, however, found to increase in interest as I advanced; and from the nature of the subject, and the number of consi-

derations connected therewith, I became involved in a long and important inquiry; an inquiry progressively developing new features, and admitting of no curtailment except only in such matters as did not directly bear upon the subject. As it is, I fear I have but imperfectly discharged the duty entrusted to my care; it is, however, done honestly; and trusting to future developments in the hands of superior writers, I close the report under the impression that the preceding investigations may direct public attention to the extension of our knowledge and improvement of our practice in the combustion of fuel and the prevention of smoke.

Since the foregoing was written—upwards of eleven years ago—considerable improvements and advances have been made by a great number of persons to remedy the evil and suppress the nuisance of smoke. Local Acts of Parliament, almost without number, have been obtained for this purpose, and the hands of municipal and corporate bodies have been strengthened for the more perfect attainment of these objects. Almost every town of importance in the kingdom, where steam-engines are employed, or manufactures are carried on, have powers and clauses in their local acts to enforce the observance of the required conditions for the abatement of the nuisance; we are, however, still far short of the panacea or cure for the evil; and although we might enumerate almost a hundred professional remedies, how very few of them do effectually succeed! This is probably not so much the fault of the doctor as the malignant character of the disease; and we have yet to learn whether this want of success arises from want of skill or defects in the process adopted, or, what is equally probable, from gross mismanagement on the part of those who have charge of the furnace.

The cause of these differences are questions not easily answered, but all appear to agree that the thing can be done, and the great problem for solution is, how to do it. If we ask Jukes, Prideaux, Hall, Hazeldine, and many others, we are at once referred to their respective friends and advocates, and

upon inquiry we find that each of them answers admirably well. Nevertheless, in the face of all these assertions, and the actual demonstrations we have received, there is something wrong, something defective, which renders the whole of their projects, to a great extent, abortive. Now, to remedy these evils is the great question for solution; it is still an open question, and one well deserving attention.

Repeated attempts have certainly been made to remove, or at least to mitigate this nuisance; and the authorities of most large towns have been active in their endeavours to suppress it. It is probably more offensive to the sight than injurious to the health; but judging from appearance, it is destructive of vegetable life, and productive of the worst consequences as regards the purity of the atmosphere; it hangs, like a black mantle, over the sites and precincts of our large towns; and viewing it in this light, it is most desirable (by some means or other) to have it removed.

The difficulties which surround this important question, appear to arise, not so much from a want of knowledge of the principle upon which the cure should be effected, but from the difficulty in finding workmen calculated to carry the required measures into effect. This appears to be the more singular, as some workmen seem to perform the duty required of them in a very creditable manner, and that more particularly when they are watched and carefully inspected to see that they do their duty. Now it is a question of deep interest to know what is the cause of this, and in my endeavours to effect a change for the better, I have recommended to the civic authorities at Glasgow and Liverpool to hold out premiums and rewards to engineers and stokers for the disappearance of smoke in their respective establishments, and that just and equitable fines should be imposed when that is not effected, and along with it a saving of fuel.

These measures have been enforced in a joint report drawn up by Mr. Leslie of Edinburgh, Mr. Johnstone of Glasgow, and myself, addressed to the Dean of Guild, at the instance of that functionary against Messrs. Todd and Higginbottom of that

city, for a nuisance in one of their chimneys emitting large volumes of smoke in the immediate neighbourhood of a large and populous district.

In addition to the suggestions contained in the Glasgow Report*, I shall conclude by directing attention to the following rules appended to a similar Report addressed to the Corporation of Liverpool. These have been submitted to the public as recommendations to be observed in the management of the furnace; and assuming that the instructions therein given are carefully attended to, we may reasonably look forward to a considerable abatement of the nuisance.

Recommendations for the Prevention of the Smoke Nuisance.

1st. Enginemen and stokers should be instructed to charge their fires, commencing from the end nearest the bridge; and before throwing coal on the furnace, the incandescent or partially burnt fuel must be spread, in order effectually to cover the grate-bars, and prevent the admission of a surcharge of cold air between them at any uncovered part.

2nd. The draught of the furnace may be regulated by the damper, which, in slow combustion, is only raised a few inches, in order to retain the heat as long as possible in the flues and round the boiler, time being an element in combustion. *Where active firing* is required, and the charges of coal are made in varying quantities and at intermittent intervals, doors on the ash-pit and slides to regulate the supply of air to the gases will be preferable to the use of the damper.

3rd. The furnace or grate-bars should be kept clean and free from clinkers, for the purpose of admitting as much air as may be necessary to combine with the solid or incandescent fuel; and a sufficient number of orifices should be made at the door for the admission of the required supply of air to effect the combustion of the *gaseous* portion of the coal evolved in the chamber of the furnace, and above the fresh charge.

* Vide Appendix, No. VI.

4th. In every case where it can be accomplished, the boilers, steam-pipes, and every part exposed to the atmosphere should be carefully clothed and covered with non-conducting material to prevent the escape of heat.

5th. In all cases of active combustion, the system of the diffusion of air through the furnace-doors, behind the bridge, or in both, should be used to prevent the air having a cooling effect.

6th. In the construction and erection of boilers, the pyrometer and sight-holes should be used: the first to ascertain the varying temperatures in the flues, the admission of air and mode of charging the furnace; and the second, to enable the fireman to observe the varying internal state of the flues and furnace, either as regards combustion, flame, or smoke.

Lastly. Proprietors of steam-engines should ascertain by experiment the quantity of coal necessary to perform a given quantity of work; and the engineer, or those responsible for the working of the boilers, should be allowed a premium on the quantity of coal saved, and be subject to a proportionate fine for neglect, or for permitting the appearance of smoke*.

* In order to render the first recommendation more explicit, I have shown in the annexed figure the most approved method in use for charging the

furnace. A represents the covering of fresh fuel, B the incandescent fuel, and D the brick bridge over which the gaseous products pass into the flues.

Note by Mr. Fairbairn, being an Appendix to the preceding.

During the progress or about the close of the above Report, I found that my friend and former pupil, Mr. A. Murray, had communicated a paper on a similar subject to the Institution of Civil Engineers, entitled "The Construction and proper Proportion of Boilers for the Generation of Steam."

Mr. Murray has had many opportunities of judging of the best forms and proportions of marine boilers, and, from the facilities afforded in his professional avocations at the Royal Dockyard, Woolwich, I am induced to quote a few of his observations relative to the area of the flue, bridge, chimney, &c., which have in some degree been omitted in the preceding Report. In treating of the quantity of air entering into combination with the volatile products of pit coal, Mr. Murray states, that "The quantity of air chemically required for the combustion of 1 lb. of coal has been shown to be 150·35 cubic feet, of which 44·64 enter into combination with the gases, and 105·71 with the solid portion of the coal. From the chemical changes which take place in the combination of the hydrogen with oxygen, the bulk of the products is found to be to the bulk of the atmospheric air required to furnish the oxygen as 10 is to 11. The amount is therefore 49·104. This is without taking into account the augmentation of the bulk due to the increase of the temperature. In the combination which takes place between the carbon and the oxygen, the resultant gases (carbonic acid gas and nitrogen gas) are of exactly the same bulk as the amount of air, that is, 105·71 cubic feet, exclusive, as before, of the augmentation of bulk from the increase of temperature. The total amount of the products of combustion in a

In this diagram it will be seen, that before firing, it is necessary to spread the incandescent fuel over the surface of the grate-bars, so as to prevent the admission of too much cold air in that direction. This being accomplished, the fresh coal is then thrown on, commencing at the bridge D, and working backwards towards the front, until the charge is completed.

cool state would therefore be $49{\cdot}104 + 105{\cdot}71 = 154{\cdot}814$ cubic feet.

"The general temperature of a furnace has not been very satisfactorily ascertained, but it may be stated at about 1000° Fahrenheit, and at this temperature the products of combustion would be increased, according to the laws of the expansion of aëriform bodies, to about three times their original bulk. The bulk, therefore, of the products of combustion which must pass off must be $154{\cdot}814 \times 3 = 464{\cdot}442$ cubic feet. At a velocity of 36 feet per second*, the area, to allow this quantity to pass off in an hour, is ·516 square inch. In a furnace in which 13 lbs. of coal are burnt upon a square foot of grate per hour, the area to every foot of grate would be $\cdot 516 \times 13 = 6{\cdot}708$ square inches; and the proportion to each foot of grate, if the rate of combustion be higher or lower than 13 lbs., may be found in the same way.

"This area having been obtained, on the supposition that no more air is admitted than the quantity chemically required, and that the combustion is complete and perfect in the furnace, it is evident that this area must be much increased in practice where we know these conditions are not fulfilled, but that a large surplus quantity of air is always admitted. A limit is thus found for the area over the bridge or the area of the flue immediately behind the furnace, below which it must not be decreased, or the due quantity could not pass off, and, consesequently, the due quantity of air could not enter, and the combustion would be proportionally imperfect. It will be found advantageous in practice to make the area 2 square inches instead of ·516 square inch. The imperfection of the combustion in any furnace, when it is less than 1·5 square inch, will be rendered very apparent by the quantity of carbon which will rise unconsumed along with the hydrogen gas, and show itself in a dense black smoke on issuing from the chimney. This would give 26 square inches of area over the bridge to every square foot of grate in which the rate of combustion is 13 lbs.

* See Dr. Ure's experiments, read before the Royal Society, June 1836.

of coal on each square foot per hour, and so in proportion at any rate. Taking this area as the proportion for the products of combustion immediately on their leaving the furnace, it may be gradually reduced as it approaches the chimney, on account of the reduction in the temperature, and, consequently, in the bulk of the gases. Care must, however, be taken that the flues are nowhere so contracted, nor so constructed, as to cause, by awkward bends or in any other way, any obstruction to the draught; otherwise similar bad consequences will ensue."

From this statement it would appear that 26 square inches of area over the bridge is about the correct proportion for the combustion of 13 lbs. of coal per hour on each square foot of grate-bar. Now these proportions are rather more than are given in stationary boilers, as the mean of a number of experiments, taken where the combustion was most perfect, gave about 18 square inches over the bridge, and about 28 square inches as the area of the flues to every square foot of grate-bar.

These data may not at first sight appear important; they are, however, of great value in practice, as the economy of the fuel and the efficiency of the furnace in a great measure depend upon the height of the bridge behind, which operates as a retarder of the currents, in the same way as the damper is used for checking the draught of the chimney in the flues.

Mr. Murray further treats of the temperature of the furnace, flues, &c., but these points having already been experimented upon and fully discussed in the Report, it will not be necessary to notice them in this place.

LECTURE V.*

ON THE NECESSITY OF INCORPORATING WITH THE PRACTICE OF THE MECHANICAL AND INDUSTRIAL ARTS A KNOWLEDGE OF PRACTICAL SCIENCE.

If I possessed a command of language capable of rendering what I have to communicate tolerably attractive, I should probably have less difficulty in making the subject, on which I venture to address you, clearly and explicitly understood. I appear before you at the request of the Directors of this Institution, and I hope, notwithstanding the defects under which I labour, to be able to engage your attention on a subject of some importance, inasmuch as its true appreciation may lead to results in every sense calculated to improve our practice and enlarge our conceptions in the pursuit of our respective callings.

In attempting to investigate the present state of our knowledge of the constructive arts, I have been induced to believe, that, although we may be considered to rank amongst the first in the art of mechanical design and construction, we are, nevertheless, not the first in some other departments of the useful arts. To make our position more clearly known, I shall endeavour to point out wherein our superiority consists, and wherein I consider we are behind the inventive talent and practice of other countries.

There cannot exist a doubt that we are far from perfect and have much to learn in this respect. The Great Exhibition of

* Delivered, at the request of the Directors, to the Members of the Manchester Mechanics' Institution, March 1852.

last year directed public attention to our position as an industrial people, and one of the beneficial results of that immense and varied collection of constructive art is observable in the notice which the subject is now beginning to receive in quarters best calculated to direct the public taste, and encourage a better and purer style of construction. It is a singular but an important fact, in countries where the industrial arts are cultivated with the greatest success, that the principles on which they are founded should be so imperfectly understood. How very few of our best practitioners in Architecture, Civil and Mechanical Engineering, are acquainted with the rudiments, or even with the simplest theoretical rules of their professions; and how often have they to depend upon chance, instead of sound elementary knowledge, for the various constructions on which they elaborate defective, if not abortive results! I have myself laboured, and still labour, under these disadvantages, and it is from a consciousness of this deficiency that I now address you. I do so under the impression that our successors may attain greater distinction, and greater certainty, in the strength, beauty and proportion of their constructions, than we have hitherto been able to accomplish. At the present moment, and for many years past, we have suffered severe inflictions on our national pride, in being called upon to witness failures and abortions in the art of construction, which a cultivated taste, superior skill and extended knowledge would have prevented. This is a national reproach, and the example of the past will continue to be the rule of the future, so long as we have to grope our way in the dark, under the guidance of prejudice and ignorance, instead of being governed by sound principles and correctly determined laws calculated to produce very different and much happier results.

To render the subject on which I purpose to address you as intelligible and as explicit as possible, I shall adopt the useful practice of dividing it into heads, as follows:—

I. On the necessities which exist for a knowledge of science in union with practice.

II. On the importance of national schools and institutes for imparting scientific knowledge to foremen and managers of works.

III. Educational institutions established on the continent of Europe and America.

IV. Differences of scholastic institutions in this as compared with those of other countries.

V. On the comparative state of our manufacturing industry as applied to cotton, during the last and the present centuries.

VI. The increase of other branches of industry in a similar ratio to that of cotton.

Lastly. Self-acting machines, and their application to constructive science.

I. *On the necessities which exist for a knowledge of science in union with practice.*

It is extraordinary, that in this country—which, above all others, is famed for the extent of its manufactures, mechanical skill, and extensive practice in the useful arts—there should be no institute, nor any establishment whatever to teach and instruct the rising generation in the elementary rules of their respective professions: these, of all others, are the most important to the community, and the best calculated to enhance the value, and extend the influence of our industrial resources. In my opinion, every one should be taught the rudiments and higher branches of their professions upon the same principles as barristers or physicians are taught, and, with this difference only, that no man should be ineligible to practise his profession, whenever he finds himself competent to the discharge of its duties; any enactment to the contrary would militate against the freedom of labour and the employment of capital, and if carried out would paralyse the best interests of a manufacturing and commercial community. Every person intended for professional pursuits in connexion with the art of construction, should have a theoretical as well as a practical education. They should be taught the fundamental rules connected with their respective professions, or at least so much of theory as would enable them

to enter upon the practice with some degree of certainty, and that more especially in the practical development of those principles on which the safety of the public and the success of their professional career depend.

It is absurd to talk against theory, as if a knowledge of the exact sciences was a dangerous and a useless attainment; nothing can be more erroneous than this impression, as on close inspection there is no practice without theory, any more than there is no effect without a cause. In the useful arts, theory can only be considered dangerous when it is not reducible to practice, and the real meaning of the term *theory*,—which creates so much alarm in the minds of practical men,—is neither more nor less than a series of definite rules by which practice is governed, and through which we derive, from fixed and definite laws, those sound and definite results, which of all others it is the primary object of practice to accomplish. In the Mechanical Arts how difficult, precarious and unsatisfactory are the thoughts of men unacquainted with first principles, and how very often does that deficiency lead them into mal-construction and those errors which a knowledge of science would teach them to avoid! It is true, that some of our first engineers and some of our most ingenious mechanicians have been men of limited education—men of humble origin, but how much more perfect would have been their labours had the emanations of their minds and their subsequent constructions been based upon the unerring laws of natural science!

A knowledge of the exact sciences must be valuable under every circumstance of life, and this knowledge when united to sound judgement is irrevocably the forerunner of a sound and perfect construction. I could multiply examples where ignorance—as a pretender to knowledge—has been productive of the most untoward results, not only in abortive attempts at construction, but in those on which the lives and property of individuals depend. It is not an uncommon occurrence to witness in works of this kind the most glaring imperfections, a waste of material, and a total want of proportion

arising from the absence of this knowledge; and in order to lessen the number of those discrepancies, our practical men should be educated, and that education should be accompanied with the conviction that sound practice can never be attained without some definite rule for its guidance. Fully impressed with these views, and the advantages to be derived from theory in the exercise of a well-founded practice, I shall endeavour to prove from evidence which I possess, that theory and practice are the twin sisters of science, and cannot be separated without endangering the connexion, or destroying the beauty, harmony and solidity of construction.

II. *On the importance of national schools and institutes for imparting scientific knowledge to foremen and managers of works.*

Before I direct your attention to the facts which I propose to lay before you, I would first advert to the present inefficient state of our educational resources, the imperfect means we have at our disposal, and the advantages we might derive from well-conducted and well-organized institutions, such as are now established and hold out encouragement to aspirants for scientific distinction in other countries. It is essential to the prosperity of every country,—and to none more so than our own,—that the industrial arts should be carefully nursed and cultivated with energy in every department, and by the introduction of increased intelligence, every endeavour should be made to perpetuate to succeeding generations an improved and healthy progression.

To effect these desirable objects, we must rear for future service a more intelligent and better educated class of foremen, managers and workmen. We must enlarge their sphere of action, and prepare them by suitable instruction for their respective callings. We must offer them, at a cheap rate, such rudimentary and theoretical knowledge as will qualify them for the due and faithful performance of their duties, and thus raise them to a higher standard of character, both as individuals, or members of the community. To elevate the mind and improve the intellectual character of the rising generation

must be a work of time, but the necessities of the age demand increased intelligence in our workshops, and in every other department of our national industry; and any attempt to improve the condition and enlarge the mental capacities of that important class, must eventually lead to the best results.

It is evident to every reflecting mind that society never stands still; there is a restless activity abroad; and if ever we become stationary, it is easy to foresee that others will reap the harvest of our past labours, and be first in the race of national supremacy.

It is true we have our Mechanics' Institutes, Athenæums, Lyceums, and many similar institutions, which do honour to the country; but they are so constituted, or perhaps the persons for whom they were instituted are so constituted, as to justify the observation that they have failed to serve the particular classes for whom they were originally intended, and they have probably been still less efficient as regards the advancement of the industrial arts. We are still in want of institutions and museums for scientific and industrial tuition, and until such institutions are established in the metropolis and in some of the large towns, and in active co-operation with the middle and working classes themselves, we may look in vain for that combination of talent, in theory and practice, the want of which must sooner or later seriously affect the destinies of our manufacturing and mechanical industry.

III. *Educational institutions established on the continent of Europe and America.*

Let us now examine what has been done and what is now doing in other countries by means of educational institutions of practical science; and suppose we select the "Conservatoire des Arts et Métiers" at Paris, because from this we may learn our own deficiencies, and the evils we are suffering in perpetuating errors and abortions in construction, which a very small share of rudimentary knowledge would quickly remedy. The "Conservatoire des Arts et Métiers" originated first with Descartes, and subsequently with Vancauson about the year 1775, and from

that time up to the present it has received the support of the different governments that have ruled France. It is now under the superintendence and direction of Colonel (now General) Morin, one of the highest scientific authorities of that country.

Colonel Loyd—one of the special Commissioners of the Great Exhibition—in his letter to Lord Granville, says, "That the lessons we have learned in passing through the extensive galleries of that college* must have impressed on the mind of every visitor the great superiority in education which France thus possesses for the industrial classes; and in connexion with the still more extensive branches of instruction in the 'Ecole des Arts et Métiers,' it will go far to discover to us why a nation so close to our shores still maintains, in several classes of manufactures and design, a superiority over the artists and workmen of our own country." From this it would appear that almost any young person in France has excellent opportunities at command for obtaining both theoretical and practical knowledge in all the departments of the sciences. He can study at his leisure the progressive improvements that have taken place in the different machines connected with the manufactures, and he has before him practical illustrations and practical specimens of materials, including models of machines and tools of every description, which are here deposited and reserved for purposes of instruction.

Colonel Loyd again observes, that "Education is so cheap, that the acquirement of high scientific knowledge in connexion with interesting demonstrations and manipulations of all descriptions becomes to the youth of France so fascinating, that at an early age they often pass an examination showing such high qualifications in both science and the arts, that the services of these young men are sought for by all the manufacturing countries in Europe."

Now what is to prevent our having similar institutions? Why cannot we add to the native energy and skill of our own

* On the occasion of a visit of the Royal Commission and Jurors of the Great Exhibition to Paris, August 1851.

artificers, that amount of knowledge of the exact sciences which would enable them to pursue their different avocations, not only with greatly increased certainty and effect, but with all the advantages which a system of instruction in practical science is calculated to produce, and which would ultimately extend itself into every branch of the industrial and the useful arts? This might certainly be accomplished, provided we had a more general system of national education; a system, sanctioned by all classes of the community, adapted to the intellectual wants of the people, and such as would sink all religious differences in the advancement and improvement of the community.

But what does Dr. Lyon Playfair say upon the subject, in his inaugural address at the opening of the Museum of Economic Geology? In quoting from Liebig, he observes, that "the great desideratum of the present age is practically manifested in the establishment of schools in which the natural sciences occupy the most prominent places in the course of instruction. From these schools a more vigorous generation will come forth, powerful in understanding, qualified to appreciate and to accomplish all that is truly great, and to bring forth fruit of universal usefulness. Through them, the resources, the wealth and the strength of empires will be incalculably increased. Institutions such as these are not substitutes for, but supplementary to our universities. It is the industrial training which we profess to give, and nothing else, which is subsidiary to that object. Not that we do or should forget abstract science as such, because I believe the discoveries in abstract laws are of more real benefit to industry than their immediate application." It is thus that the lecturer reasons on the necessity of union between the scientific and the practical student, and I sincerely believe that there is yet before us a coming age when the exact rules of physical truth will be brought to bear upon the constructive and useful arts, with the same certainty and effect in the practical operations of the artificer and the mechanic, as they now do in the laboratory of the chemist or the observatory of the astronomer.

Now in order to acquire these important desiderata, we must

educate and elevate the intellect of the industrial classes to a higher standard of scientific acquirement than that which at present exists, and we must give to the mechanics and artisans of these islands the same facilities for obtaining knowledge as exist in other countries. This, you will observe, cannot be accomplished without schools; and unless something is shortly done, we shall rather recede than advance in the great road of improvement.

I have already stated that the French had long witnessed, not without interest, the wants of the rising generation, particularly as respects a more extended knowledge, and a sounder education for those persons destined to follow industrial occupations. To meet these wants, the "Conservatoire des Arts et Métiers" was established. Professors were appointed to give lectures and instruction in arithmetic, elementary geography, weights and measures, statics, descriptive geometry, stone-cutting, carpentry, cabinet-makers' work, perspective mechanics, transmission of motion, hydrodynamics, including descriptions of instruments of all kinds, designing—plain and ornamental, machinery, architecture, and many other important subjects, at a cheap rate. These comprise a course of instruction given to upwards of 300 students, who receive an education fitting them for situations in the higher branches of construction, in the military as well as the civil professions, and hence arises the superior knowledge in that country which is brought to bear upon the useful arts.

But even this school was not sufficient to meet the growing demand for knowledge in France, and some years since it was followed by another, entitled the Central School of Arts, "*Ecole centrale des Arts et Manufactures.*" In this school the middle classes receive an excellent education, and some of the most distinguished men in France, such as Olivier, Martelet, Masson, Dumas, Bélanger and many others, do not hesitate to give lectures and conduct the different branches of practical science.

In other countries, besides France, the same attention has been bestowed upon the education of the mechanic and the

artisan. Prussia is famed for its educational institutions, and the Government, in its solicitude for the well-being of society, renders it imperative that every person in the Prussian dominions should be educated. A distinguished writer, speaking of societies, says that "associations for occasional discussion, of men pursuing the same or similar studies, have long been found advantageous for the intercommunication of the difficulties, the doubts and the discoveries of students. In more recent times, when each art has gradually connected itself with the sciences on which its success depends, the importance of these meetings has become obvious to the manufacturer, although in this country it may not have become apparent to the statesman."

In these sentiments we have every encouragement for intercommunication and discussion, and I cannot too forcibly impress upon your minds the necessity which exists for forming yourselves into societies for mutual instruction.

IV. *Differences of scholastic institutions in this as compared with those of other countries.*

The Accademia del Cimento of Italy, the Royal Society of London, the Academy of Sciences at Paris, have had a long series of imitators in the principal cities of the civilized world. The increasing extension of science, and the wants of its cultivators, have led them to a subdivision of their pursuits, and to form societies generally devoted to each separate department of science. The diffusion of scientific knowledge, so graphically described by Babbage, is still far short of the objects it is desirable to attain. In this large and important manufacturing district, we have no museum of the arts and manufactures, no collection of the various raw materials so extensively consumed, no depositary for models or machines for illustration, and no public professors to direct and demonstrate the truths of natural science. Everything is left to the novitiate himself, and provided he is ardent and enthusiastic, he may rise to distinction by the force and energy of his own mind; but very limited indeed is the assistance he is likely to derive from the institutions of his country. I have myself contended against, and overcome to a certain

extent, the struggles and difficulties which always beset the early and also the after-life of the self-taught aspirant in the walks of science; and fully persuaded that these difficulties frequently overpower the good resolutions of the student at the very threshold of his labours, I am the more anxious to see them removed, and at the same time to see established in this city* an industrial museum and institute calculated to meet the wants of the public, and to afford to our successors those advantages of elementary instruction which have unfortunately been denied to ourselves, but which are imperative for securing the ascendency and success of our manufactures in every branch of industry.

I will not detain you with further observations on this part of the subject; suffice it to observe, that I entertain hopes that the Great Exhibition, so recently closed, has not only shown what can be done by united efforts, but has imparted a stimulus that has been felt in the remotest parts of the kingdom; and this will, I trust, not only inspire the public mind of this district with a desire to erect, but liberally to endow an institution which will promulgate the truths of science, and enlarge the field of observation in every department of industrial pursuit, and which in future ages will speak well for the talent and industry of our times.

I have now to direct your attention to a few remarks on those constructions which have done so much for the country, and which now afford employment to so many thousands of persons in these districts.

V. *On the comparative state of our manufacturing industry as applied to cotton, during the last and the present centuries.*

Before entering upon the more immediate objects which I have selected for your consideration in the next lecture, permit me to offer a few observations on a subject exceedingly interesting, and to which I beg to direct your attention. If we take, I will not say a statistical, but a very cursory view of the present position of Manchester, and compare it with what it

* Not only in Manchester, the city to which I refer, but in many towns in the kingdom, having a claim to an improved and general system of education.

was at the close of the last and the commencement of the present century, we shall find that at that period the useful and industrial arts were comparatively of little importance. We shall also find that the germs of a new, and above all others, an important branch of manufacturing industry, were springing into existence. I have no correct returns of the state of our manufacturing industry at that period, but the writings of one of the earliest and most intelligent spinners, Mr. John Kennedy of Ardwick, to whom this country is indebted for many improvements in machinery, inform us that the spinning of cotton-yarn, antecedent to the year 1768, was of an exceedingly limited description. That gentleman, in his account of the rise and progress of the cotton trade, states that the hand-loom, as a machine, remained stationary for a great number of years without any attempts at improvement, until 1750, when Mr. John Kay, of Bolton, first introduced the fly-shuttle, and that the spinning of cotton-yarn, until that period and for many years previous, was almost entirely performed by the family of the manufacturer at his own house. This united and simple process went on till it was found necessary to divide their labours, and to separate the weaving from the spinning, and that again from the carding and other preparatory processes. This division of labour, as Mr. Kennedy truly says, led to improvements in the carding and spinning, "by first introducing simple improvements in the hand instruments with which they performed these operations, till at length they arrived at a machine, which, though rude and ill-constructed, enabled them considerably to increase their produce." Thus it was that improvements and the division of labour first led to the factory system, and to that splendid and extensive process, which, at the present moment and for many years to come, will affect the destinies of nations, both as regards their political and commercial prosperity.

From 1750 to 1770, when Mr. Hargreaves, of Blackburn, first introduced his spinning jenny, by means of which a young person could work from ten to twenty spindles instead of one, there was little or no change; but a very material alteration

took place shortly after the introduction of these improvements, which were immediately followed by Mr. Arkwright's machinery for carding and roving*. These, accompanied by the introduction of Mr. Crampton's mule in 1780, may be justly considered as the origin of the factory system,—a system which has grown to such colossal dimensions, as to render it one of the most important and most extensive branches of manufacture ever known in the history of ancient or modern times.

"Mr. Arkwright built his first mill at Cromford, in Derbyshire,"—I again quote from Mr. Kennedy,—"in 1771. It was driven by water; but it was not till 1790, or some time after, when the steam-engine of Watt came into use, that the cotton trade advanced at such an accelerated speed, as to render its increase and present magnitude almost beyond conception. This immense extension is not only a subject of deep interest to the philosopher and statesman, but one which is likely to furnish a large field of observation for the future historian of his country."

I will not trouble you with the statistics of the cotton trade as it now exists, but simply observe—as many of you are, doubtless, better informed on this subject than myself—that I am within the mark, when I state, that not less than 31,500 bales of cotton are consumed weekly in the two kingdoms of England and Scotland; that nearly twenty-one million spindles are almost constantly in motion, spinning upwards of 105,000,000 hanks, or 50,000,000 miles of yarn per day, in length sufficient to circumscribe the globe 2000 times. Out of this immense production about 131 millions of lbs. of yarn are exported; the remainder is converted into cloth, lace, and other textile fabrics. This

* Through the kindness of my friend Mr. Kennedy, I have now in my possession an account of the Trial in the Court of King's Bench to repeal a Patent granted on the 16th of December, 1775, to Richard Arkwright, for an invention of certain instruments and machines for preparing silk, cotton, flax, and wool for spinning. This trial took place at Westminster on the 25th of June, 1785, and closed on the 14th of July of the same year, when the Court gave judgment to repeal the Letters Patent.

marvellous increase, this immense extent of production, could not be effected without considerable changes in the prospects of the moral as well as the physical condition of society. It has entirely changed the position of the resident population of the district; and the secluded valleys, farm-houses, and neat cottages, —the beauties of a Lancashire landscape of the last generation,— are rapidly giving way to the conversion of villages into populous towns, with innumerable erections, which resound with the busy hum of the spindle and the shuttle.

Along with these changes, we perceive a new generation springing into existence. Factories, steam-engines, and tall chimneys rising in every direction, and the noise and smoke which meet the eye and the ear of the stranger at every step, give evidence of the activity and prosperity of the industrious hive, which, at some future period of English history, will announce to succeeding generations the inventions and the discoveries of the nineteenth century.

In this attempt to place before you a short and succinct account of the rise and progress of our national industry, I must not forget that yarn, however finely and dexterously spun, is not cloth; and here we enter upon another and equally ingenious process. The yarn must be woven before it is fit for use, and we shall find weaving one of the most interesting as well as one of the most elaborate operations of the useful arts. I need not inform you how the ancient Hindoos, Egyptians, and probably the early Chinese, converted their yarn into cloth. The Indian and Oriental department of the Great Exhibition exhibited the rude and primitive character of their looms and other implements of manufacture which have been handed down from generation to generation, from the earliest periods, without change or improvement, to the present day. Looms of this rude construction were introduced into Europe during the first glimpses of civilization, and for many centuries even the most advanced nations were content to use the same instruments almost without improvement, until the introduction of the flying shuttle, and the subsequent inventions of Watt and

Arkwright, opened a new and untrodden field for improvements in every department of art and manufacture.

Power-looms at that period were unknown, and although attempts were made by Dr. Cartwright, as early as 1774, to convert the hand-loom into a machine to be moved by power, it was not until the beginning of the present century that the power-loom assumed its present form and presented that intelligence of structure which rendered it self-acting, and enabled it successfully to compete with the hand-loom process. From that time, about 1810 to 1812, we may date the commencement of the great increase in this important branch of our manufactures.

The improvements introduced by Mr. Bennet Woodcroft and others for weaving twills and similar fabrics created new expedients and applications, and greatly increased the demand for this description of manufactures; whilst the invention of Jacquard for weaving figured cloth startled every one by the facility of its application, and the extreme ingenuity and beauty with which it accomplished the almost perfect development of that description of manufacture.

The increase and extent of cloth manufactured from power-looms may be estimated from the official returns kindly furnished me by Mr. Leonard Horner, the intelligent Factory Inspector. There are now at work in the United Kingdom about 250,000 power-looms; and as each loom will, upon the average, produce from five to six pieces of cloth per week, each piece being 28 yards long, say 25 yards a day per loom, we shall then have 250,000 $\times 25 = 6{,}250{,}000$ yards, or 3551 English miles of cloth per day, equal to the distance between Liverpool and New York. Only think of the importance of such an enormous extent of manufacture; a manufacture that employs upwards of 12,000 hands in weaving alone; supplying from that source—the power-loom—an annual produce of cloth that would extend over a surface, in a direct line, of upwards of 1,000,000 miles! These statistical returns are important and interesting, as they show the extent to which the manufactures of the country have been carried.

VI. *The increase of other branches of industry in a similar ratio to that of cotton.*

In my endeavours to trace the advances made in the cotton trade, I have not attempted to enumerate the various circumstances which have influenced the improvements and extension of that manufacture; nor is it my intention on this occasion to notice the almost equally important advances which have taken place in other textile fabrics, such as may be seen in the linen, silk, woollen and mixed goods manufactures. From all these springs of industry have flowed innumerable benefits; and notwithstanding the accelerated speed at which the industry of the country is moving, we have only to instance the constant increase of the populous towns of Lancashire and the West Riding of Yorkshire, particularly Bradford, Huddersfield and Halifax, to arrive at the conclusion, that, although much has been done, much has yet to be accomplished before the supply equals the demand. The principal object, however, which I have in view in this address is, in addition to education, to direct attention to the art of construction in those important branches of art, on which, in a great measure, the prosperity of our manufactures depends; and also to those great sources of national wealth,—railways and steamboats; and it will afford me unmixed satisfaction, if, in the observations I have to offer, there should be found such an amount of practical and useful knowledge as may lead to the improvement and extension of those industrial resources to which I have devoted so many years of my experience.

It must appear obvious to those who have studied and watched attentively the unwearied exertions and continued advancement which have signalized the energies of our engineering and mechanical industry, and the difficulties and dangers, however formidable, that have been encountered and surmounted by the indomitable spirit, skill and perseverance of the British engineer, that the ingenuity and never-failing resources of our mechanical population are not only the sinews of our manufactures, railways and steamboats, but the pride and glory of

our country. It is for this important class that I have ventured to address you, and I trust the time is not far distant when we shall witness establishments suitable for their education; an education, which above all others will teach them to reason and to think, and give a more correct knowledge of physical truth. To these we may add a clearer conception of the varied forms and manipulations of art, including those other springs of industry in which the true interests of the country consist.

On this subject I have endeavoured to lay before you such views as I consider necessary for the improvement and increased prosperity of a class that requires instruction, and further, to raise them in their moral and social condition to a higher standard of character than they at present occupy. In support of these views, I have submitted for consideration the importance of early training, the want of institutions with competent masters, and the necessity which still exists for a better acquaintance with natural science. To these I have directed your attention in order to ensure an enlarged and better system of instruction, and at the same time to make every individual of this class intelligent as well as useful members of the community. Now this desirable object cannot be accomplished by schools or schoolmasters alone; we must ourselves sympathise with the teachers, and depend upon our own resources, if we desire to attain the elements of instruction as well as their practical application. We must bring the whole powers of the mind to bear upon the subject we wish to learn; we must reason and think, and accustom ourselves to the exercise of those powers of analysis which are calculated to remove difficulties, and to pave the way by inductive reasoning and simple demonstration for the attainment of truth. Let me point to one or two examples in the history of distinguished men to show what has been done by those who have laboured in the field of science, and who have attained an honourable position by their unflinching perseverance in the cultivation of the useful arts. Most of you are doubtless acquainted with the early difficulties which beset the career of the journeyman printer, Benjamin

Franklin, but which were overcome by his perseverance and never-tiring industry; and you have heard how James Ferguson, when a shepherd-boy in Aberdeenshire, used to lie on his back in the winter nights with an old blanket about him, and map the stars as they passed the meridian. James Watt, by the resources of his own mind and a knowledge of physical truth, made himself an imperishable name in the walks of practical science, and conferred upon mankind that multiplying and inestimable blessing, the steam-engine, which, though in its infancy, is changing the relative condition of mankind, is bringing within our reach the productions of every land, and is doubtless destined to work out for the human race still greater wonders. To these great men may be added the names of my highly-respected friends, the late John Dalton and George Stephenson; both of them taught in Nature's school, and who, entirely dependent on their own resources, have won a place in the niche of fame.

These are examples which, with many others that might be mentioned, I could wish you to follow; they are worthy of imitation, and your efforts in search of knowledge, if characterized by the same determined perseverance, will be equally successful. Let not, however, a want of success at the commencement deter you from the pursuit. We cannot all be great men; but every man, whatever may be his condition in life, may derive benefit from a knowledge of nature's laws and their application to our physical wants.

Having thus far shown the necessity for study and application in the pursuit of knowledge, let us now see how it can be applied amongst the varied forms and conditions of our industrial establishments. To every reflecting person it must be evident, that an educated man skilled in his trade, with a knowledge of the laws on which it is founded, and of steady habits, is much more valuable to his employer and himself, than the mere workman whose actions are akin to those of a machine, whose mind is a waste, and who seldom thinks. The first, as an intelligent being, is sure of employment, and the

best and most difficult operations will be entrusted to his care; he attains the confidence of his employer, probably becomes a foreman, and ultimately he acquires a share in the business, or sets up for himself. How many deserving young men have done this! How many have I myself recommended to situations of trust; and how many from small beginnings and little promise have risen to distinction in their respective professions!

On this part of the subject I have, however, said enough to convince you of the importance of a useful and virtuous education, and I shall now conclude with a brief notice of the rise and progress of our engineering and mechanical establishments, and the encouraging prospects which improved training in the different departments and processes of our manufactures is likely to open out in the country.

VII. *Self-acting machines, and their application to the construction of machinery.*

It is nearly half a century since I first became acquainted with the engineering profession, and at that time the greater part of our mechanical operations were done by hand. On my first entrance into Manchester, there were no self-acting tools; and the whole stock of an engineering or machine establishment might be summed up in a few ill-constructed lathes, and a few drills and boring machines of rude construction. Now compare these with any of the present works, and you will find a revolution of so extraordinary a character as to appear to those unacquainted with the subject scarcely entitled to credit. The changes thus effected, and the improvements introduced into our constructive machinery, are of the highest importance; and it gives me pleasure to add that they chiefly belong to Manchester, they are of Manchester growth, and from Manchester the greatest numbers have had their origin. It may be interesting to know something of the art of tool-making, and of the origin of machines, which by an almost creative power in themselves have contributed so largely to multiply the machinery of manufactures, as well as the construction of other machines employed in practical mechanics. In Manchester,

the art of calico-printing was in its infancy forty years ago; the flat press, and one, or, at the most, two coloured machines were all that were then in use; the number of those machines is now greatly multiplied, and I believe some of them are capable of printing eight to ten colours at once*; and the arts of bleaching, dyeing and finishing have undergone equal extension and improvement.

There were only three or four establishments that could make a steam-engine, and those were Bolton and Watt of Soho, Fenton, Murray and Wood of Leeds, and Messrs. Sherratts of this town. The engines of that day ranged from 3 up to 50, or at most 70 horse-power; now they are made as high as 500, or in pairs from 1000 to 1200 horse-power. An order for a single engine at that time was considered a great work, and frequently took ten or twelve months to execute; now they are made by dozens, and with such despatch, that it is no uncommon occurrence to see five or six engines of considerable power leave a single establishment in a month.

In machine-making the same powers of production are apparent. In this department we find the same activity, the same certainty of action, but with this difference,—that the smaller machines are manufactured more rapidly and in greater numbers than can possibly be done in the larger and heavier description of work. The self-acting, turning, planing, grooving and slotting machines have afforded so much accuracy and facility for construction, that the mechanical practitioner is able to turn, bore and shape with a degree of certainty almost amounting to mathematical precision. The mechanical operations of the present day could not have been accomplished at any cost thirty years ago, and what was considered impossible at that time is now performed with an intelligence and exactitude which never fail to accomplish the end in view, and reduce the most obdurate mass to the required consistency in all those forms so strikingly exemplified in the workshops of engineers and machinists.

* I have just been informed that printing machines are now constructing to print fifteen colours at one process.

To the intelligent and observant stranger who visits these establishments, the first thing that strikes his attention is the mechanism of the self-acting tools, the ease with which they cut the hardest iron and steel, and the mathematical accuracy with which all the parts of a machine are brought into shape. These performances are now effected to an enormous extent, and the American system of *Dummies* recently introduced by our ingenious friend Mr. Anderson of the Arsenal, Woolwich, is a powerful indication of what can be done in the manipulation and management of a well-devised and well-constructed establishment. When these implements are carefully examined, it ceases to be a wonder that our steam-engines and machines are so beautifully and correctly executed. We perceive the most curious and ingenious contrivances adapted to every purpose, and machinery which only requires the attendance of a boy to supply the material, and to apply the power which is always at hand.

In conclusion, I would observe that it is an honour to this country that we stand at the head of the engineering and mechanical profession. It is an art—I would call it a science—which has occupied the attention of the greatest men from the days of Galileo and Newton down to those of Smeaton and Watt, and it now receives attentive consideration from some of the ablest and most distinguished men of the present age, such as Poncelet, Morin, Humboldt, Brewster, Babbage, Dr. Robinson of Armagh, Willis and many others.

A great deal has been done, but a great deal more may yet be accomplished; and provided that deficiency can be supplied by suitable institutions calculated to store the minds of our foremen and operatives with useful knowledge, affording them opportunities essential to its acquisition, I can see no reason why a better system should not be adopted: a system that is calculated to produce considerable modifications, and effect improvements in the moral as well as the intellectual condition of that important class. In the attainment of this object, let us endeavour to engraft on our system of training theory in conjunction with practice, and to bring the philosopher

into close connexion with the practical mechanic*. This connexion will remove prejudices, and encourage a sounder system of management in every description of manufacture: it will moreover encourage an improved taste in novelty and design; promote more perfect practice, and engender ideas less speculative, but more in accordance with correct principles,—the true pioneers and harbingers of success. When this is accomplished, we shall no longer witness abortions in construction, but a carefully well-digested system of operations, founded on the unerring laws of physical truth.

* The annual meetings of the British Association for the Advancement of Science have greatly improved the notions of theoretical as well as practical men. These meetings have afforded incalculable benefit to the practical engineer and mechanic. They bring all his projects and contrivances under the strict rules of science, and on the other hand they bring the abstract theorist to the test of practical experience.

LECTURE VI.

METALLIC CONSTRUCTIONS*.—ON IRON SHIP BUILDING.

To the student in architecture, engineering and building, there is scarcely any acquirement more essential to professional success than a knowledge of the properties of the materials used in construction. It is equally important in the art of design as it is in correctness of proportion: whether the structure be a house, a ship, or a bridge, we must, before entering upon its construction, and before we can attain a due and correct idea of proportion, as a preliminary inquiry, make ourselves acquainted with the material of which it is composed. We must also make ourselves acquainted with its powers of resistance to the varied strains of tension, torsion and compression; and further, we should know something of its elasticity, and its powers of restoration under the varied tests and changes to which it may be subjected. All this knowledge we should know and apply in such a manner as will best meet the requirements of construction, and that without incurring

* At the commencement of these lectures it was intended to have given a series of communications on construction, where iron, as a material, has been chiefly employed. The subject was, however, found to embrace such a large field of inquiry, and my time was so closely engaged in other professional duties, that I was forced to abandon the idea, and content myself with the inquiry into the strength and other proportions of the iron ship. Whether another opportunity will present itself for a more extended investigation, I am unable to say; I will, however, bear it in mind, and I trust the time may shortly arrive, when my engagements may admit of sufficient leisure for effecting that object.

the charge of an unnecessary or wasteful expenditure of material. Very little reflection will show this knowledge to be indispensable before we can attain anything like perfection; and in fact, no professional rank can be attained by the architect, engineer, or builder, unless he is acquainted with sound principles of construction, and with the properties of the material in which he deals.

Assuming, therefore, that the necessity exists for an increase of this knowledge, I shall endeavour to lay before you in a tabulated form, such amount of experimental research as directly bears upon the art of construction; and although these experiments are confined almost exclusively to metallic substances, I shall nevertheless add a few others, exhibiting the strength, &c., of different kinds of timber, occasionally used in combination with iron, but more frequently as a perfectly independent material applied to the useful arts.

Viewing the subject in this light, I shall first direct your attention to the resisting powers of cast and wrought iron to different kinds of strain, and subsequently to timber and such other material as we find in general use in the art of building and construction.

Resisting powers of cast iron.

From a number of carefully conducted experiments on cast iron, I have selected the following results. They are the highest in the order of their powers of resistance to a transverse strain, and as in each instance the bar is reduced to exactly one inch square, the results may fairly be estimated as a criterion of the resisting powers of the different irons of Great Britain.

TRANSVERSE STRENGTH of cast-iron bars 1 inch square, 4 ft. 6 in. between the supports.

	Name and No. of Iron. The letter C signifies cold blast, H hot blast.	Breaking weight in lbs.	Deflection in inches.	Power to resist impact.	Remarks.	Quality.
Welsh.	Ponkey ....3 C	581	1·747	992	Whitish grey.	Hard.
	Beaufort ....3 H	517	1·599	807	Dullish grey.	Hard.
	3 C	448	1·726	747	Bright grey.	Hard.
	Mean.........	515	1·691	848·6		
English.	Low Moor ....2 C	472	1·852	855	Dark grey.	Soft.
	Butterly .... H	502	1·815	899	Dark grey.	Soft.
	Elscar ....2 C	427	2·224	992	Grey.	Soft.
	Old Park ....2 C	485	1·621	718	Grey.	Soft.
	Mean.........	471	1·778	863·5		
Scotch.	Muirkirk ....1 C	418	1·570	656	Bluish grey.	Soft.
	Carron................3 C	443	1·336	593	Grey.	Soft.
	Monkland ....2 H	403	1·762	709	Bluish grey.	Soft.
	Gartsherrie ....3 H	447	1·557	998	Light grey.	Soft.
	Mean.........	428	1·556	739		

From the above it will be perceived that the average transverse strength of eleven specimens of English, Welsh and Scotch iron is 471 lbs. on 1 inch square bars, 4 feet 6 inches between the supports. These again give a mean deflection of 1·675 inches, and a power to resist impact of 817.

Similar irons will resist a tensile strain and a crushing force per square inch as follows.

EXPERIMENTAL RESULTS to determine the ultimate powers of resistance to a tensile and crushing strain.

Description of iron.	Tensile strength per square inch of section.	Height of specimen.	Crushing strength per square inch of section.	Ratio of tension to compression.
	tons.	inches.	tons.	
Low Moor No. 2	6·901	1½	41·219	1 : 5·973
Clyde No. 2	7·949	1½	45·549	1 : 5·729
Blenavon No. 2	7·466	1½	45·717	1 : 6·123
Brymbo No. 3	6·923	1½	34·356	1 : 4·963
Mean.........	7·309	1½	41·710	1 : 5·707

In the foregoing experiments, the Clyde and Blenavon

indicate the greatest powers of resistance, either as regards a tensile or a crushing strain.

In addition to the irons given above, which are those in common use, Mr. Stirling's mixed or toughened iron exhibits considerably increased powers of resistance to every description of strain when compared with the unmixed irons. Mr. Stirling has patented a process for mixing a certain portion of malleable with cast iron, and when carefully fused in the crucible or the cupula, the product will resist a tensile strain of nearly 11 tons per square inch, and a compressive one of upwards of 60 tons, the specimens being 1½ inch long and 1 inch square. This mixture, when judiciously managed and duly proportioned, increases the strength about one-third above that of ordinary cast iron.

As the strength of wrought iron is not only a subject of great interest at the present moment, but is likely to become more so every year, I shall have to trespass longer upon your attention than may be agreeable. It is, however, imperative that I should do so, as I shall have occasion before the close of these remarks to refer to facts, and to deduce therefrom conclusions for the elucidation and illustration of my subject.

The importance of an inquiry into the art of ship-building will be appreciated by you all, and when you bring to mind the dreadful casualties of navigation, the hardships of shipwreck, and the horrors of fire, you will admit the vast importance of selecting the strongest and safest materials for the construction of our ships.

It is chiefly for this reason that I have selected this subject, and ventured to impose upon your attention a few dry figures, in order that you might become acquainted first of all with the strength and natural properties of the materials of which ships are ordinarily composed, and secondly, to attach due weight to their judicious application and distribution in the attainment of a powerful, buoyant and durable structure. I would not have ventured upon this critical and difficult subject without some practical experience, but having taken an active part as well as

a deep interest in the earliest stages of the application of iron as a material for ship-building, and having, until within the last two years, been extensively engaged as a practical builder, I am perhaps the better able to offer a few suggestions on the advantages and superiority of iron in our war as well as in our mercantile marine.

It is well known to the public that the naval department of the Government abandoned a few years back—I think prematurely, if not improperly—the construction of iron vessels as ships of war. The Admiralty, in my opinion, arrived at a very hasty conclusion in condemning the use of iron after the very limited number of experiments which had been tried upon iron targets and old iron vessels, as the dangerous effects of shot might have been mitigated by extended practice, and many improvements and suggestions might have taken place to remove the objections, and ensure greater confidence in the construction. At several of these experiments I was present, and although the results were certainly unexpected, and perhaps discouraging, yet they did not, in my opinion, justify the entire abandonment of a material, not only the strongest and lightest for such a purpose, but offering the greatest possible security under all ordinary and many extraordinary circumstances. Even in war steamers, when in action, the chances are in favour of the iron ship, as it is not only secure from fire, but is much stronger, and will sustain more strain when assailed by storms and hurricanes than any other description of vessel, however strongly built. Propulsive power is another element in our war marine. Steamers can back out of difficulties and dangers when sailing vessels must remain exposed; they can assail the enemy at a greater distance, and take up any position consistent with the emergency of the case, and with their great guns and long range, inflict severe punishment and do great execution without receiving—under these circumstances—a single shot. Speed being thus admitted to be an important element in our war marine, the iron ship, from its lightness and buoyancy, has another evident advantage over the wooden one, as an equal amount of power will propel it

faster through the water, and hence follow the advantages peculiar to this construction.

In the event of war it is essential that the steam marine of this country should have great command of power to enable the ships to manœuvre at sea with almost the same precision as a squadron of horse on parade. They should have the power to advance and retreat as circumstances may require, and the new system of tactics which must eventually come into operation should inspire the same confidence in the crew as it would do in the commander, namely, that the iron steamer is not only formidable in war, but safe under all circumstances of attack or defence.

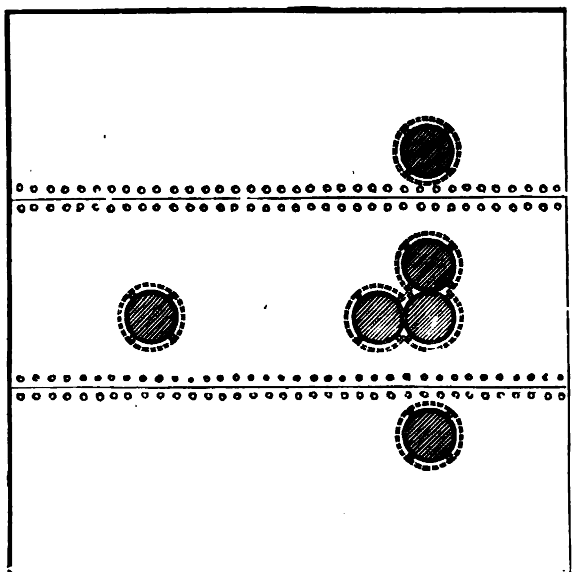
In our mercantile marine we are progressing with better prospects and greater certainty, but the decision of the Admiralty to limit the construction of iron vessels to the mail and packet service, is, according to my views, a retrograde movement, and to say the least of it, inconsistent with the onward tendencies of a healthy progression. I trust the Lords Commissioners of the Admiralty will not only see the importance, but the absolute necessity of rescinding that order, and that we shall not only witness the introduction of iron for that service, but more particularly when steam power is employed in all and in every condition of an effective and a safe marine.

The effects of shot on iron vessels.

As respects the effects of shot upon iron vessels, (a circumstance which led to the above decision on the part of the Admiralty) although at first sight alarming, they are, on more mature consideration, such as might reasonably be expected. A number of experiments were undertaken some years since at the Arsenal, Woolwich, to determine the effect of shot upon the hull of an iron vessel, and also with the view of providing means for stopping the passage of water in the event of the vessel receiving a shot below the water line. The gun used in the experiment was a 32-pounder placed at a distance of 30 yards from the targets, and was loaded at the commencement with the full charge of 10 lbs. of powder. Subsequently it

was reduced to 8, 6, 4, 2 and 1 lbs. to produce the effect of distance in a short or long range. I assisted, at the request of the late Admiral Sir George Cockburn, at those experiments, and the results, some of which I may venture to mention, were

Fig. 1.

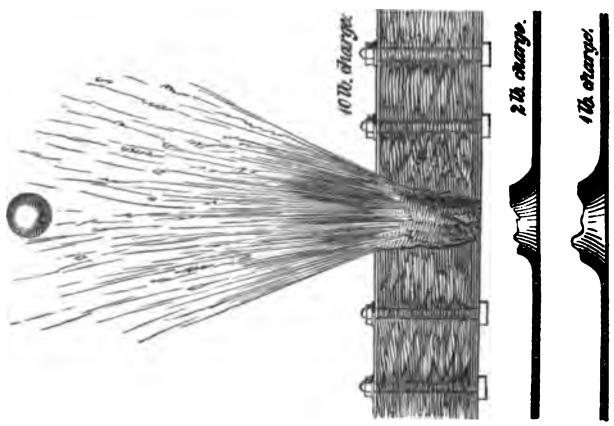


exceedingly curious and interesting. The initial velocity of the ball, 6 inches in diameter, with a full charge of 10 lbs. of powder, is about 1800 feet per second, and with 2 lbs. of powder about 1000 feet.

In these experiments there were five or six targets about 6 feet square, composed of different thicknesses of plates and variously arranged, so as to represent in effect as well as in appearance a portion of the side of an iron ship. Diagrams are here exhibited to represent a side view and sections of the plates and fastenings of the targets, and the effects produced by the shot as it passed through the plates, and also in three or four other experiments, through a lining of India-rubber and cork dust, specially introduced to prevent the dispersion, and arrest the progress of the splinters as they were driven forward by the effects of the shot.

Fig. 1.—Represents a side view of the target with the effects of six shots at various velocities through it. Fig. 2 shows the effect of a shot with a charge of 10 lbs. of powder through three thicknesses of $\frac{1}{2}$-inch plates, and figs. 3 and 4 the effect of

Fig. 2. Fig. 3. Fig. 4.



a 2lb. and 1 lb. charge through a single $\frac{1}{2}$-inch plate, with ribs of the usual construction*.

I should not be justified in going into further details on this subject at present, and must confine myself to general terms. On some future occasion I may, however, be enabled to resume the inquiry, which is one of considerable interest and of great public importance.

Whilst laying before you such information as I possess on the subject of iron ship-building, it is not my intention to trench upon the province of the marine architect as respects the forms, lines or other details required in construction. That field is already occupied by men of great experience and superior talent, and the only one to which I would more immediately direct your attention is that which refers to the proportion of the parts, the distribution of the material, and the equalization of the powers of resistance to strain in the different parts and positions of the structure. These are considerations which, in a greater or less degree, affect almost every description of mecha-

* See Appendix, No. V.

nical construction, and we cannot be far wrong if on this occasion we endeavour to supply such experimental knowledge as we possess to the improvement of this important art.

If we study the art of construction as exhibited in the laws of nature, we shall find endless varieties of form. In the animal and vegetable kingdoms there is no waste of material. Every animal and every plant is adapted to its purpose, its organization is perfect in every respect; every joint, muscle and fibre is suited to the work it has to perform, and the utmost harmony in proportion, beauty of design, as well as economy of material, is discernible in every construction that emanates from the hand of nature's Architect. In that school we are sure to learn under the tuition of that great Teacher in every department of art, and by a careful study of those laws which open upon us at every page, we can scarcely fail to apply them to some good and useful purpose.

With such examples before us, and with such a wide and wonderful range of objects, why should we commit blunders and hesitate when we should analyse and investigate? There is no mechanism so intricate, but we find its compeer in nature, and where we may find a rule for our guidance. We have only, therefore, to study Nature in her varied forms and conditions to arrive at sound conclusions either as regards the examples that are set before us, or the approximation to laws which govern all constructions.

Our present object is, however, limited to the inquiry into the laws which guide the experienced ship-builder in the prosecution of his art: it will be proper in the first instance to ascertain the nature and strength of the material he may choose to employ, in order to show in what way it should be disposed to produce at a minimum cost the greatest possible effect. For these objects I am fortunate in having before me a long series of experiments which I made for the same object more than ten years ago*. These facts are given in Appendix I., but to save trouble in the reference I have considered it necessary to lay

* See Philosophical Transactions, Part II. 1850, and Appendix, No. 1.

before you the following short abstracts which I trust may prove equally beneficial in this as they have been in other constructions.

In the resistance of wrought-iron plates we have in these experiments, which were made on five different sorts of iron, the tensile strengths in tons per square inch as follows:—

	Torn asunder in direction of the fibre. Tons.	Torn asunder across the fibre. Tons.
Yorkshire plates	25·770	27·490
Yorkshire plates	22·760	26·037
Derbyshire plates	21·680	18·650
Shropshire plates	22·826	20·000
Staffordshire plates	19·563	21·010
Mean	22·519	23·037

These results give a mean power of resistance of nearly 23 tons per square inch. And the ratio 22·5 : 23, gives about $\frac{1}{45}$th in favour of those torn across the fibre.

In following up similar investigations on timber, I found, according to Professor Barlow of Woolwich, that the cohesive strength of different kinds of hard wood were—

	lbs.		lbs.
Box	20·000	Beech	11·500
Ash	17·000	Oak	10·000
Teak	15·000	Pear	9·800
Fir	12·000	Mahogany	8·000

Assuming Mr. Barlow to be correct, and taking the mean strength of iron plates as given in the experiments at 49,656 lbs. to the square inch, or say 50,000 lbs., we have the comparison between wood and iron in the following ratios of resistance to a tensile strain:—

	Ratio. Timber. lbs.		Ratio. Iron. lbs.		Ratio, timber representing unity.
Ash	17·000	:	50·000	or as	1 : 2·94
Teak	15·000	:	50·000	or as	1 : 3·33
Fir	12·000	:	50·000	or as	1 : 4·16
Beech	11·500	:	50·000	or as	1 : 4·34
Oak	10·000	:	50·000	or as	1 : 5·00

Hence it appears that malleable iron plates are five times

stronger than oak, or in other words, their powers of resistance to a force applied to tear them asunder, is as 5 to 1, making an iron plate $\frac{1}{2}$ inch thick equal to an oak plank $2\frac{1}{2}$ inches thick.

As a further guide to the knowledge of the strength of materials used in construction, some curious and interesting experiments were made to ascertain the resistance of wrought-iron plates to indentation or pressure by a blunt instrument with a hemispherical end, 3 inches in diameter, forced through the plate until it was burst*. The results are

	lbs.	Mean.
Experiment 1st. A plate $\frac{1}{4}''$ thick burst with	13·789	16·779
Experiment 2nd. A plate $\frac{1}{4}''$ thick burst with	19·769	
Experiment 3rd. A plate $\frac{1}{2}''$ thick burst with	37·519	37·723
Experiment 4th. A plate $\frac{1}{2}''$ thick burst with	37·928	

Here it will be observed, the strengths are nearly in the ratio of the thickness of the plates, a half-inch plate requiring double the force to produce fracture. Similar experiments were made on oak timber, and here the resistance follows the ratio of the squares of the depths, and a $\frac{1}{4}$-inch thick plate is able to resist a force equal to that required in the rupture of a three-inch oak plank.

The results are—

	lbs.	Mean.
Experiment 1st. An oak plank 3 inches thick was burst with..	18·941	17·933
Experiment 2nd. An oak plank 3 inches thick was burst with..	16·925	
Experiment 3rd. An oak plank $1\frac{1}{2}$ inch thick was burst with..	4·532	4·406
Experiment 4th. An oak plank $1\frac{1}{2}$ inch thick was burst with..	4·280	

Here the strengths to resist bursting or crushing are as the squares of the depth.

Let us now take the comparative resistance of wrought iron per square inch to a direct crushing force, and we have from

* The details of these experiments will be found in the Appendix, No. I., page xxxii. They refer to the resistance of plates forming the hull of a ship. They exhibit the resistance of those parts to compression, when acted upon by a round hard substance, such as rocks or stones when the vessel takes the ground, either in tidal harbours or any other position with uneven surfaces calculated to injure the ship.

the experiments of Rondelet and Professor Hodgkinson the following ratios:—

Specific gravity.	Description of materials used.	Resistance per square inch of timber in lbs.	Resistance per square inch of wrought iron in lbs.	Ratio of strength. Timber representing unity.
7·700	Wrought iron.	......	70·00	......
·560	Yellow pine.	5375	70·00	1 : 13·02
·540	Cedar.	5674	70·00	1 : 12·33
·580	Red deal.	5748	70·00	1 : 12·16
·640	Birch.	6402	70·00	1 : 10·93
·660	Sycamore.	7082	70·00	1 : 9·88
·753	Spanish mahogany.	8198	70·00	1 : 8·53
·780	Ash.	8683	70·00	1 : 8·06
·700	Dry English oak.	9509	70·00	1 : 7·36
·980	Box.	9771	70·00	1 : 7·16

From the above we have the relative resisting powers of the different kinds of timber; also the specific gravities of each, which enables us to determine the comparative weights, as well as strengths of wood and iron respectively.

In marine constructions, where the material is iron, our knowledge of its resisting powers would be incomplete, if we did not consider it in all its bearings as regards its application to ship-building. It is unlike timber which has to be caulked between the joints; the principle is not union, but a tendency to force the parts asunder. Now in the joints of the iron ship this is quite the reverse, for the joints of an iron vessel are so constructed as to form a solid mass of plates, which, if well riveted, will resist forces, such as the action of heavy seas, that no timber-built ship, however well and however strongly constructed, would ever be able to withstand. The iron-built ship, when constructed with butt joints with interior covering plates and a smooth exterior surface, is superior as regards strength, buoyancy and lightness to any other vessel of whatever material it may be composed, and our practice in the mercantile marine has proved this to be the case. In all these combinations, it is, however, a desideratum to have the joinings of the parts, and the connexions as near as possible of equal strengths. This in practice cannot always be accomplished; but with due regard to a correct system of riveting, and

careful formation of the joints, a near approximation to uniform strength may be obtained. As a practical guide to these objects, I shall append a short summary of the experiments indicating the relative strengths of different forms of riveting, and in what they differ from the strength of the plates, taking the whole as one continuous mass without joints.

The results obtained from forty-seven experiments on double and single riveting are here recorded:—

No. of Experiment.	Cohesive strength of plates. Breaking weights in lbs. per square inch.	Strength of single-riveted joints of equal section to the plates taken through the line of the rivets in lbs. per square inch.	Strength of double-riveted joints of equal section to the plates taken through the line of rivets in lbs. per square inch.
1	57·724	47·743	52·352
2	61·579	36·606	48·821
3	58·322	43·141	58·286
4	50·983	43·515	54·594
5	51·130	40·249	53·879
6	49·281	44·715	53·879
7	43·805	37·161	......
8	47·062	......	......
Mean......	52·486	41·590	53·635

The relative strengths will therefore be—

For the plate 1000
Double-riveted joint 1021
Single-riveted joint 791

which shows that the single-riveted joints have lost one-fifth of the actual strength of the plates, whilst the double-riveted joints have retained their resisting powers unimpaired. These are convincing proofs of the superior value of the double-riveted joints; and in all cases where strength is required, this description of joint should never be omitted.

In a previous analysis the strengths were as 1000:933 and 731, but taking the mean we have 1000 : 977 and 761 for the double-riveted and single-riveted joints respectively. From these we must, however, deduct 30 per cent for the loss of metal actually punched out for the reception of the rivets, and the absolute strength of the plates will then be to that of the riveted joints as the numbers 100, 68 and 46. In some cases, where the

rivets are wider apart, the loss sustained is not so great; but in iron ships, boilers and other vessels which require to be water-tight, and where the rivets are closer to each other, the edges of the plates are weakened to that extent. Taking, however, into consideration the circumstances under which the results were obtained, as only two or three rivets came within the reach of experiment, and taking into account the additional strength which might be obtained by an increased number of rivets in combination, and the adhesion of the two surfaces of the plates in contact*, we may reasonably assume the following proportions, which, after making every allowance, may fairly be considered as the relative values of the strength of wrought-iron plates, as compared with their riveted joints :—

Taking the strength of plates at	100
We have for the double-riveted joint	70
And for the single-riveted joint	56

The resisting powers of riveted joints (such as are used in vessels required to be steam-tight or water-tight, and exposed to a pressure varying from 10 to 100 lbs. on the square inch) are therefore as the numbers given above, and in all these constructions it may be useful, when calculating the strengths, to make the necessary deductions for the loss sustained in the union of the plates.

Having thus established correct data as respects the strengths of materials, either single or in combination, we shall have less difficulty in their application to the construction of vessels exposed to severe strains, such as boilers, bridges or an iron ship ; and notwithstanding the boasted declaration that the "wooden walls of Old England" are our surest defences, we shall not, in my opinion, seriously injure, but greatly benefit our position, by pinning our faith to the iron walls as a material of equal, if not of much greater security. To this I am satisfied we shall shortly arrive, provided we persevere in the use of a material calculated eventually to supersede every other in the construction of vessels intended for strength and the maintenance of the British marine.

* The adhesion is given in some experiments by Mr. E. Clarke.

In the construction of iron ships, three important considerations present themselves:—

1st, Strength and form.

2nd, Security.

Lastly, Durability.

In treating of the first of these divisions—*strength and form*—it will be necessary to ascertain for what purpose the vessel is to be used, what seas it has to navigate, and what description of work it has to perform. Let us assume it to be one of the Atlantic or other great ocean steamers, and we have a model both in form and tonnage that would become equally formidable as a war steamer, or useful and commodious as a packet calculated to shorten the distance between the extreme points of a lengthened voyage.

In these considerations, as before stated, it is not my intention to enter upon the subject of modeling, or that form of vessel best calculated to offer the least impediment to the ship's progress, such as the lines of least resistance, and other points which bear more directly upon the form at the bows and stern, than upon the question of durability and strength. These belong more properly to the naval architect or ship-builder than to the engineer, whose knowledge may, however, be advantageously employed in determining the best and most judicious application of the material. And certainly I may confidently assert that I know of no construction which affords a wider scope for the exercise of sound and scientific judgment, or which demands more minute and accurate attention, than that of the hull of a ship, which in its several parts ought assuredly to possess nearly uniform strength.

To this important part of the question I would direct your careful attention, in order to consider it in all those varied forms and conditions to which vessels are subjected under strain; whether arising from tempestuous seas, or from stranding, under circumstances where serious damage occurs, but where wooden vessels are in danger of going to pieces, and, as it not unfrequently happens, are entirely lost. In the former case, as

in a tempest, or tornado under the tropics, where wooden vessels are often severely strained, there is much to be feared; but in the iron ship, if properly constructed, we have greatly increased security, and, provided we assume such vessel in its best construction, and regard it simply as a huge hollow beam or girder, we shall then be able to apply with approximate truth the simple formula used in computing the strengths of the Britannia, Conway, and other tubular bridges.

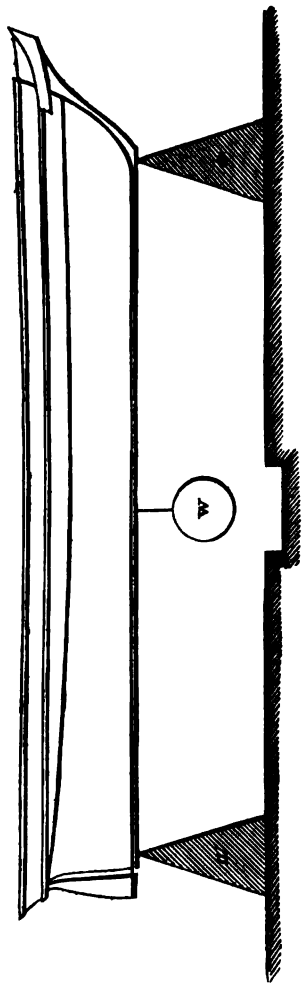
Let us, for example, suppose a vessel of similar dimensions to the Great Western (the first steamer that successfully crossed the Atlantic), 212 feet long between the perpendiculars, 35 feet beam and 23 feet from the surface of the main deck to the bottom of the sheathing attached to the keel. Now, considering a vessel of this magnitude, with its machinery and cargo, to weigh 3000 tons, including her own weight, and supposing in the first instance that she is suspended on two points resting on the bow and stern at a distance of 210 feet, as shown at fig. 5, we should then have to calculate from some formula yet to be ascertained by experiment, the ultimate strength of the ship.

To determine this formula with accuracy is a work of research: in the meantime, we are fortunate in having before us that which applies with so much certainty to tubular bridges and tubular girders; and all that is required in this case will be to ascertain the correct sectional area of the plates to prevent the tearing asunder of the bottom, and the quantity of material necessary to resist the crushing force along the line of the upper deck on the top. It is true that the necessary data have yet to be determined, but the iron ship-builder cannot be far wrong if he assumes the breaking weight in the middle, at the point W, fig. 5, to be equal to the united weights of ship and cargo. This, in the case before us, would give an ultimate power of resistance of 3000 tons in the middle, or 6000 tons, equally distributed along the ship with her keel downwards. On some future occasion I may possibly revert to this subject; it is one of great interest, and not unworthy of a series of well-conducted

experiments to determine the laws of greatest resistance, and the principle upon which iron ships should be built.

Assuming the tests, or the calculations derived therefrom, to be correct, let us now reverse the strains, and bring the vessel into a totally different position, as in fig. 6, having the same weight of cargo on board, and supported by a wave, which for

Fig. 5.



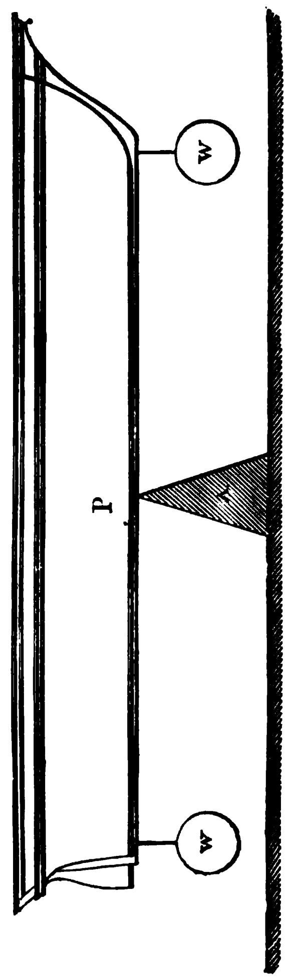


Fig. 6.

the sake of illustration we may consider as resting upon a single point, as at P, in the middle.

In this position we find the strain reversed, and in place of

the lower part of the hull of the ship being in a state of tension, it is, on the contrary, in a state of compression, and the whole of those parts below the neutral axis are subjected to that strain. On the other hand, the upper part is in a state of tension, and that tension, as well as the compressive strain below, will be found to vary in degree in the ratio of the distances from the centre of the natural point A, fig. 6, round which the two forces of tension and compression revolve. In this supposed position we may venture to calculate the strengths, as I have been in the habit of doing, in order to ascertain the limit or maximum of security, and act as if the vessel was placed in trying circumstances, either contending with the rolling seas of a hurricane, or suffering the actual suspension of either portion when taking the ground. In these critical positions, we arrive at the conclusion, that calculations founded upon the formula for wrought-iron tubular beams will determine the strength and resisting powers of an iron ship, and that under every contingency and every circumstance in which the vessel can be placed. Moreover, it will give a wide margin of security under all those forms and conditions of peril to which every vessel navigating the ocean is exposed. I am fully aware that many thousand vessels are now afloat that would not stand one-third of the tests which I have taken, but that is no reason why we should not endeavour to effect a more judicious distribution of material, and produce a maximum strength, where the lives and fortunes of the public are at stake.

Our next consideration, which is closely allied to the last, is *Security*.

On this question we have fewer difficulties to contend with; and so far as regards construction, I have endeavoured to show, that, in order to build a ship on principles as near perfect in regard to security as circumstances will admit, she must be built with such material, and upon such foundations, as are calculated to withstand the trials I have supposed her to bear. Exclusive, however, of the simple strength of the hull, there are other considerations which require attention, such as the danger

from fire, leakage, or total shipwreck. In naval constructions we have three elements to contend with, fire, air and water; and although we may effect in iron constructions extraordinary of powers resistance as respects the two latter, we are, nevertheless, subject to considerable risk as regards the former. It is true, the hull of an iron ship will not burn, but the interior fittings, which are chiefly composed of wood, if once ignited, might destroy everything on board, unless the necessary precautions are taken by iron bulkheads to cut off the communication from one division to another. In my own experience as a builder of iron vessels, I have found these bulkheads of inestimable value. They not only strengthen the ship transversely, but in case of injury to any part of the hull, any one of the divisions or compartments might be filled with water, and perhaps even the contents of that part burnt, without endangering the ship. These divisions, in fact, should be so arranged as to ensure the vessel floating under circumstances of irreparable damage to any one of those compartments, and at the same time to afford protection to those on board. Again, in case of fire—in the lamentable position in which the "Amazon" was placed—it might be advisable to have the extreme stem and stern bulkheads made double, with an air space between them, and a valve in each to fill them with water up to the line of immersion, and thus prevent the division plates on that side clear of the fire from becoming red-hot, and igniting the timber fittings of that part, which for the time might form a place of refuge. Much may be done in this way to mitigate, if not to avert, the calamitous and fatal consequences which ensue on those occasions. Bulkheads of this description, coming up to the underside of the upper deck, might obstruct, to some extent, the communication between decks from one compartment to another; but I believe a sufficient freedom of access from one part to another might easily be effected by well-constructed iron doors, to be closed in case of accident, which would thus become effectual barriers to the fire spreading over the ship.

In carrying these objects into effect, we must not only recur to the use of iron in every case where packet-ships and steamers are employed, but they apply with the same force to Her Majesty's Navy, and particularly to steam-frigates and ships of war with auxiliary power. It is true, that the experiments, already referred to, on the dangerous effects of shot on the iron hull, are alarming; but the amount of risk and destruction is always one of degree, and I doubt whether the effects of shot on wooden vessels are less terrible than those indicated by the experiments on the iron ship; undoubtedly bulkheads and such contrivances do more than claim in point of security a decided advantage over the wooden constructions, and we have yet to learn what remedies may safely be applied to avert the risks consequent upon the effects of shot against the sides of an iron ship. Besides, we are not yet satisfied that these effects are so dangerous as they have been represented. On the contrary, I am of opinion that they have been greatly exaggerated, and that increased experience will show that iron, under all the circumstances, affords greater security, whether for war or commerce, than any other description of material whatever. As a proof of the advantages peculiar to iron as a material for ship-building, and the greatly increased security it offers in comparison with wood, I would refer to a letter and sketch of the condition of the steamer "Vanguard*," which ran foul of a reef of rocks on the west coast of Ireland, and continued exposed to the swell of the Atlantic beating her upon them for several days with comparatively little injury, excepting only the corrugation of the plates, as shown at *a*, *a*, *a*, &c., fig. 7, in her bottom, which were dinged and distorted in every possible form, but without effecting a separation in any part of the hull. Another instance is that of the "Great Britain," which stood the action of heavy seas beating her upon the sands and rocks of Dundrum Bay for a whole winter, and that without any serious damage to the hull or any other part of the ship. These are facts which speak volumes in favour of security, and the utility of iron in

* See Appendix, No. VII.

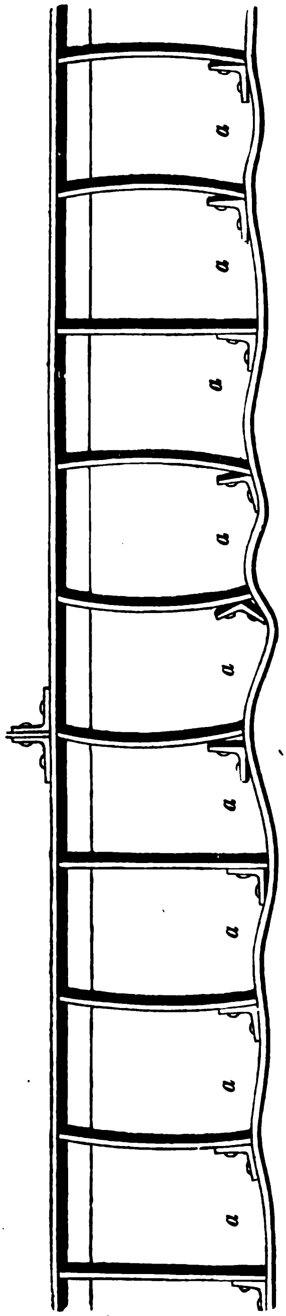
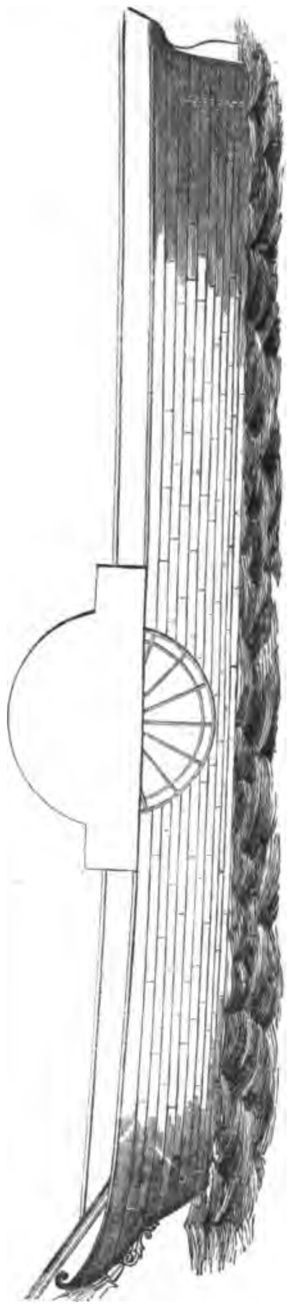


Fig. 7.



VANGUARD.

Fig. 8.

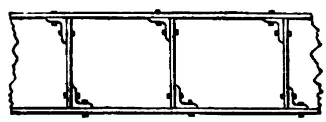
attaining that desirable object. It is true, that many objections may be urged against it when applied to certain constructions; but judging from experience, I am strongly inclined to think that we have yet much to learn, and much to accomplish in the application and distribution of iron in those constructions which more immediately apply to the security of our war and mercantile marine.

Durability.—On this part of the subject there is considerable difference of opinion, but a very cursory view of the question will at once show the great superiority of iron to timber. In another part of this communication, I have given the comparative strength of iron and the best English oak, in which it is proved that iron as a material is five times stronger than oak. This is, however, not the question which enters into the subject of durability, as the jointing of the one is incomparably superior to that of the other.

In the building of ships of the line or large merchant vessels, the keel, beams and timbers are generally of oak or teak, made of three pieces most ingeniously contrived and united by scarphs to each other to ensure strength. The ribs or frames, which are solid and close to each other, are scarphed and jointed in the same way; and the outer sheathing, which is copper-fastened, is also attached with great care, and by crossing the vertical joints of the frames great strength is obtained. The connexion of the deck beams to the frames by strong iron knees is another source of strength; but with all the care, ingenuity and skill bestowed upon this construction, it is far from perfect in point of strength. Timber-built vessels, when pitching and rolling in heavy seas, are subjected to severe strains by the changes which are constantly in operation, and which produce motion at every joint; and it not unfrequently happens that the seams open and close to an extent sufficiently decisive as to the nature of the structure and defective union of the parts. Now we may venture to state, that in the iron ship, when all the parts are soundly riveted together, there are no joints. The whole may be considered continuous, and conse-

quently there can be no yielding, except from what may be considered the elasticity of the united mass, and this, like every other kind of material, must yield to the disturbing causes which affect it. The plates of iron-built ships, it will be observed, are the same as the planking or sheathing of those built of timber, and the plates are riveted to strong iron ribs, as exhibited in the annexed cut, fig. 9, from 12 to 15 inches asunder, and answering the same purpose as the solid framing of a vessel composed of teak or oak.

Fig. 9.



On this question I will not, however, at present, attempt to go further into detail; suffice it to observe, that if the iron ship be well-proportioned in its parts, double-riveted at the joints, and the material judiciously distributed, so as to apply the greatest strength in the direction of the greatest strain, we may reasonably calculate on a perfectly secure and durable vessel.

As respects the comparative merits of wood and iron vessels on the score of durability, I am of opinion that the public has entertained very erroneous views, with reference especially to oxidation, which for the last twenty years has been the "rock-a-head" of every iron ship. The extent of this evil has been greatly exaggerated; for there are instances of several iron vessels built twenty years ago, which are still in existence, with no sensible appearance of corrosion or decay, and, what is of equal importance, without having required repairs, if we except a few coats of oil-paint, or the application of some other anti-corrosive substance to neutralize the effects of the oxygen of the atmosphere upon the material. Nature, however, comes to our assistance in this, as in almost every other attempt in the constructive arts, and seems to confirm the proverb, that a "bright sword never rusts;" for it is with iron ships, as with iron rails; when in constant use, there is little, if any, appearance of oxidation.

Taking, therefore, all the circumstances into consideration, we may reasonably conclude that much has yet to be done in this department of the useful arts; and I have no doubt that the iron ship of British origin will yet ride triumphant on every sea as the harbinger of peace, the supporter of commerce, and the great and only security of our national defence.

If, in my attempts to elucidate a subject of such vast extent, and of such great national importance as the present, I have succeeded in conveying to your minds that knowledge which it is important we all should possess, I have attained the principal object of my appearance in this place.

Bear in mind, that in every attempt to achieve success in any important undertaking, we must fortify our minds and correct our judgments with a knowledge of physical truth. There is no sound construction without it, and we have only to follow Nature, look up to Nature's laws, and apply them with careful discrimination, to arrive at the best results.

LECTURE VII.

ON STEAM.

At the request of a large and useful body of working engineers, and at the desire of several Institutions which have for their object the improvement and instruction of that important class, I have been induced to set apart a portion of my time for the study of a subject which involves considerations of much importance to the great mass of the community. If I were to state that the subject I propose to treat upon is one so easily mastered, that my past experience rendered my task an easy one, I should practise a deception towards you, and arrogate to myself a degree of information and an amount of research in physical science which I do not possess. On the contrary, it has cost me much time and labour to prepare the statements I have to lay before you; and I trust that, should these fall short of your expectations, you will kindly take the will for the deed, and extend to me that patient consideration, which a sense of my own deficiencies and the importance of the subject induce me to ask.

On a former occasion I was invited by the Committee of Management of the Union of the Yorkshire Mechanics' Institutes at Leeds to give them a lecture on boiler explosions, and in my endeavours to comply with that request, the lecture then proposed was extended to two: first, on boiler construction; and secondly, on the causes of boiler explosions.

Those lectures were attentively listened to by large audiences, and the Committee did me the honour to consider them of such importance as to have them printed and published in a cheap

form for distribution amongst the members of the institutions and the public.

In the consideration and preparation of those lectures, I found the subject gain upon me so fast, and become so exceedingly interesting, as to induce a strong desire for still further research; but my time was then much occupied with other professional duties, and I was obliged to abandon the attempt until a more fitting opportunity.

During a long and somewhat laborious professional life, I have however contrived, as a relaxation from other duties, to devote a considerable part of my leisure, and no small portion of the hours of sleep, to scientific inquiries; and finding it has done me no harm, but rather quickened the intellect, by enlarging its sphere of action, I have the less hesitation in recommending this practice to most of you, as I am satisfied you will find it productive of enjoyment as well as benefit. In early life I laboured, like some of yourselves, under many difficulties. Their causes I could not control; but experience has convinced me how much may be done by a willing mind; and with what certainty indomitable perseverance and a never-tiring enthusiasm in your pursuits will clear away all obstacles, and lead, by most satisfactory and pleasant paths, to reputation and success. In framing an occupation, or determining upon a study for the employment of your leisure time, let me recommend you to consider well first what you desire to attain. Let the object be practical and useful; then bring the whole power of your mind to bear directly upon the subject; work hard, and let not your energy be thwarted even by the taunts and ridicule which companions and fellow-labourers will oftentimes attempt to throw upon yourselves and your pursuits. Be not dismayed by early failure, nor turned aside by the tedium of mastering the drudgery of rudimentary study. The pleasures and delights of knowledge come only with a thorough understanding; and nothing valuable, least of all the treasure of a gifted mind, is to be had without labour. Nature has inculcated this principle for the moral government of man;

and though the prize may be difficult of attainment, it never fails in the end to reward the zealous labours of the inquiring student.

At the commencement of these observations, I stated that I found the investigations in which I was engaged for the Yorkshire Mechanics' Institutions so exceedingly interesting as to render further extension of time necessary for their extended development. That article, so valuable to an inquiring mind, was not, however, at my disposal; and I have therefore been compelled to postpone the inquiry from time to time until a fitting opportunity should arise for a renewal of it. This being the case, I will now endeavour to lay before you such facts as I have collected, and such as, I trust, may prove conducive to the extension of your knowledge, and useful in the daily practice of your separate callings.

It is well known to every lover of science that we are indebted to James Watt for many of the comforts and enjoyments of our social existence. To the ingenious contrivances, sound judgment, and philosophical research of that great man we owe more than I shall attempt to describe. We owe to him, in fact, *the Steam-Engine*! Now, the very word steam-engine denotes something more than a machine. It comprehends the engine in its organic construction as a machine, and it also comprehends steam, as an element of propulsion, acting upon its organization, and something to hold the steam. Upon *steam* and the *holder of steam* it is therefore my present purpose to discourse. In directing your attention to these two points, I shall endeavour to investigate such principles, and to lay before you such facts, as, I trust, may prove serviceable in the uses and application of that important element. In the first place, then, we shall confine our observations to steam; and in the second, to *the boiler or the vessel* in which it is generated.

Before entering upon the more immediate and conclusive portion of this address, it may be interesting to enumerate some of the most obvious and characteristic properties of steam.

On this subject I cannot do better than quote the language employed by Dr. Robinson, the friend and biographer of Watt, in his Treatise on Steam and the Steam-Engine. In this treatise the learned Doctor observes, that "steam is the name given in our language to the visible moist vapour which arises from all bodies which contain juices easily expelled from them by heats not sufficient for their combination. Thus we say, the steam of boiling water, of malt, of a tan-bed, &c. It is distinguished from smoke by its not having been produced by combustion, by not containing any soot, and by its being condensable by cold into water, oil, inflammable spirits, or liquids composed of these.

"We see it rise in great abundance from bodies when they are heated, forming a white cloud, which diffuses itself and disappears at no great distance from the body from which it is produced. In this case, the surrounding air is found loaded with the water or moisture which seems to have produced it, and the steam seems to be completely soluble in air, as salt is in water, composing, while thus united, a transparent elastic fluid.

"But in order to its appearance in the form of an opaque white cloud, the mixture with, or dissemination in air, *or some elastic fluid colder than itself*, seems absolutely necessary. If a tea-kettle boils violently, so that the steam is formed at the spout in great abundance, it may be observed that the visible cloud is not formed at the mouth of the spout, but at a small distance before it, and the vapour is perfectly transparent at its first emission. This is rendered still more evident by fitting to the spout of a tea-kettle a glass pipe of any length, and of as large a diameter as we please. The steam is produced as copiously as without this pipe, but the vapour is transparent through the whole length of the pipe. Nay, if this pipe communicate with a glass vessel terminating in another pipe, and if the vessel be kept sufficiently hot, the steam will be abundantly produced at the mouth of the second pipe as before, and the vessel will be quite transparent. The visibility therefore of

the matter which constitutes the steam is an accidental or extraneous circumstance, and requires the admixture with air; yet this quality again leaves it when united with air by solution. It appears therefore to require a *dissemination* in the air. The appearances are quite agreeable to this notion; for we know that one perfectly transparent body, when minutely divided and diffused among the parts of another transparent body, but not dissolved in it, makes a mass which is visible. Thus, oil beaten up with water makes a white opaque mass.

"In the meantime, as steam is produced, the water gradually wastes in the tea-kettle, and will soon be totally expended, if we continue it on the fire. It is reasonable therefore to suppose, that this steam is nothing but water changed by heat into an aërial or elastic form. If so, we should expect that the privation of this heat would leave it in the form of water again. Accordingly, this is fully verified by experiment; for if the pipe fitted to the spout of the tea-kettle be surrounded with cold water, no steam will issue, but water will continually trickle from it in drops; and if the process be conducted with the proper precautions, the water which we thus obtain from the pipe will be found equal in quantity to that which disappears from the tea-kettle.

"This is evidently the common process of distilling; and the whole appearance may be explained by saying, that the water is converted by heat into an elastic vapour, and that this, meeting with colder air, imparts to it the heat which it carried off as it arose from the heated water, and being deprived of its heat, it is again water.

"The particles of this water, being vastly more remote from each other than when they were in the tea-kettle, and thus being disseminated in the air, become visible by reflecting light from their anterior and posterior surfaces, in the same manner as a transparent salt becomes visible when reduced to a fine powder. Thus disseminated water, being presented to the air in a very extended surface, is quickly dissolved by it, as pounded salt is in water, and again becomes a transparent fluid, but of a

different nature to what it was before, being no longer convertible into water by depriving it of its heat."

It is in this way that Dr. Robinson explains the nature and properties of steam; and although a great number of the most distinguished philosophers of the last century gave the subject careful consideration, it was nevertheless reserved for Dr. Black, in his 'Theory of Latent Heat,' to explain the phænomena, and to give the subject that minute attention, which the growing interests of the steam-engine, and other discoveries in chemical science required.

In the consideration of steam generated from water at one pressure, as compared with steam generated for similar purposes at another pressure, it will be necessary, for the sake of illustration, and the more readily to distinguish the difference which exists between them, to trace water in its different stages or degrees of temperature corresponding with the varied conditions of passing from the solid to the liquid, and from the liquid to the vaporous state. These conditions have been carefully investigated by different authors; but in order to render the subject as explicit and practical as possible, it will be necessary to inquire, first, into the condition of water as it exists in its three separate forms of solidity, fluidity, and vapour; and secondly, as to the ratio of the temperature, density, and elasticity of steam when in contact with the water which produces it.

In this division of the subject we have therefore to consider,—

1. *The condition of water as it exists in its three separate forms of solidity, fluidity, and vapour**. Water in the condition of ice is a solid, transparent, and brittle substance, and may easily be produced by reducing the temperature to 32° Fahr. In this state it is lighter than the liquid water (I believe Galileo was the first to discover this fact); and hence it happens that it floats upon water, its specific gravity being to that of water as

* It will be observed that water in the solid state has considerable cohesion; in the liquid form this cohesion is greatly diminished, and it is entirely destroyed when the water is in the form of vapour.

8 : 9. The rarefaction of ice is supposed to be owing to air-bubbles which are formed in the water at the instant of freezing, and being thus considerably larger than the quantity of water frozen, it is specifically lighter.

Others, again, such as M. Mairan, attribute the increase of its bulk to a different cause; according to that author, it arises from a different arrangement of the parts of the water from which it is formed; which in the act of freezing resolves itself into crystals or filaments regularly joined at angles of 60°, and which angular disposition causes a greater increase of volume than if they were parallel. He found by experiment, the augmentation of a volume of water by freezing, in different trials, to be $\frac{1}{14}$th, $\frac{1}{18}$th, and $\frac{1}{19}$th part of that volume; and when the water was previously purged of air, only $\frac{1}{22}$nd part. This is the condition of water in the solid state; and it is curious to observe with what regularity and certainty this new condition is produced when its temperature is reduced below 32°. Elevate the temperature above that point, and you have the phænomenon of fluidity accompanied with all its attendant forms and conditions of emergence from its imprisoned state. These phænomena have been beautifully illustrated by Dr. Black in his theory of latent heat. That distinguished philosopher discovered that it was not sufficient for converting ice into water, that it be raised to a temperature in which it can no longer retain that form, as a piece of ice of the temperature of 32° will remain a very long time in air at 50° before it melts, remaining all the time at 32°, and therefore continually absorbing heat from the surrounding air until it is all melted. By comparing the time at which the ice had its temperature changed from 20° to 32°, he found it absorbed 130 to 140 times as much heat as would have raised its temperature one degree; and he found that one pound of ice, when mixed with one pound of water 140° warmer, was just melted, but without rising in its temperature above 32°. Hence he justly concluded, that water differed from ice of the same temperature by containing as a constituent a greater quantity of

heat united in such a way as not to quit it for another colder body, and therefore so as not to affect the mercury of the thermometer and expand it. This condition of the temperature, considered as the cause of heat, was investigated by Dr. Black, under the expression of *latent heat.*

If more heat is added to the water, it is no longer latent heat, but becomes sensible in its effects, by raising the thermometer, showing the degrees of redundant heat, while fluidity alone is the indication of the combined and latent heat.

Thus we have water in two distinct forms, the solid and the fluid: in these perfectly separate conditions we have the phænomena of heat exercising the same influence on water as it does on all other bodies in nature, and which never fails to produce the desired effect in change of form and other conditions, so clearly exemplified in the organization of everything which exists.

Let us now consider the phænomena which are presented to us when water passes into the state of vapour.

Water in a state of ebullition.—The conversion of ice into water brings us to that part of our subject in which we may continue to impart heat to the liquified mass, such as we see in a boiler or kettle, until it reaches the temperature of 212°, when it boils. The phænomena of ebullition or boiling are curious, as well as interesting and instructive, and it is necessary we should all become acquainted with them before we can attain a correct knowledge of the nature and properties of steam. If we take a vessel filled with water, and apply heat to its bottom and sides, we then have sensible indications by the thermometer of the rise of temperature in the fluid: continue the application of heat, and the particles of water in contact with the bottom and sides form themselves into globules, which, being of greatly reduced specific gravity, gradually ascend, until the colder stratum of water on the upper surface of the vessel robs them of their heat, and thus destroys that buoyancy which was necessary for their ascent. This may be seen by holding water in a Florence flask over a lamp, when it will be observed, some time before ebulli-

tion takes place, that the globules or bubbles are formed at the bottom, and that they rise but a short distance in the fluid before they disappear. The distances which they reach before they collapse or disappear depends upon the temperature of the fluid, but they continue to rise higher and higher until the temperature reaches 212°, when the commotion of the water becomes general, and boiling ensues*. In this state of the

* The conversion of water into steam is thus described by Dr. Robinson, in his 'Mechanical Philosophy.' In speaking of boiling water and steam, he says, that "this conversion of liquids—for it is not confined to water, but obtains also in ardent spirits, oils, mercury, &c.—is the cause of boiling. The heat is applied to the bottom and sides of the vessel, and gradually accumulates in the fluid, in a sensible state, uncombined, and ready to quit it and enter into any body that is colder, and to diffuse itself between them. Thus it enters into the fluid of the thermometer, expands it, and thus gives us the indication of the degree in which it has been accumulated in the water; for the thermometer swells as long as it continues to absorb sensible heat from the water: and when the sensible heat in both is in equilibrio, in a proportion depending upon the nature of the two fluids, the thermometer rises no more, because it absorbs no more heat or fire from the water; for the particles of water which are in immediate contact with the bottom, are now (by this gradual expansion of liquidity) at such a distance from each other, that their laws of attraction for each other and for heat are totally changed. Each particle either no longer attracts, or perhaps it repels its adjoining particle, and now accumulates round itself a great number of the particles of heat, and forms a particle of elastic fluid, so related to the adjoining new-formed particles, as to repel them to a distance about *twelve and a half times* greater than their distance in the state of water. Thus a mass of elastic vapour of sensible magnitude is formed. Being about *two thousand times lighter* than an equal bulk of water, it must rise up through it, as a cork would do, in the form of a transparent ball or bubble, and getting to the top, it dissipates, filling the upper part of the vessel with vapour or steam.

"Thus by tossing the liquid into bubbles, which are produced all over the bottom or sides of the vessel, it produces the phænomena of ebullition or boiling. Observe, that during its passage up through the water, it is not changed or condensed; for the surrounding water is already so hot that the sensible or uncombined heat in it is in equilibrio with that in the vapour, and therefore it is not disposed to absorb any of that heat which is combined as an ingredient of this vapour, and gives it its elasticity. For this reason it happens that water will not boil till its whole mass be heated up to 212°; for if the upper part be colder, it robs the rising bubble of that heat which is necessary for its elasticity, so that it immediately collapses again, and the surface of the water remains still."

heated fluid, it must be borne in mind that water will not boil unless the heat is applied to the bottom or sides of the vessel. If the heat be applied to the top of the vessel, the water will evaporate and waste away without boiling, and hence follows the necessity of applying our furnaces and heat at the right part of the boiler, which is evidently at the bottom. Heat, from its want of *ponderosity*, is highly elastic, and when enclosed in films of water in the form of globules, its specific gravity is many thousand times less than that of water. The particles of heat to a certain extent radiate from a fire in every direction, but it will be found that in open space the tendency is upwards, and that, more particularly, when imparted to water, when the globules are produced all over the bottom, and make their ascents vertically, as already described.

We may further observe, that water boils at different temperatures, according as the atmosphere is heavy or light. When the barometer is low, the fluid will boil at a lower temperature, as water at 30 inches of the barometer boils at 212°; at 28 inches it boils at 208½°; and upon the plains of Quito, where the air is attenuated and the barometer stands at 21 inches, water boils at 195°, making a difference of 17°. These are points to which I would recommend careful attention, as the temperature at which water boils has a certain relation to the pressure of the vapour which is formed, as we shall now more fully explain.

Water in a state of vapour.—Having attained the boiling-point, we now arrive at the third state of water, viz. in the shape of vapour or steam. This is a subject which we shall have to consider more minutely, and I shall therefore endeavour to make you thoroughly acquainted with all the properties of steam, particularly those relating to tension, density, elasticity, &c. We shall have the more occasion for this information, as it relates to our daily practice, and all those requirements that govern the application of steam, not only as an agent of immense force and power, but in all its varied appliances to the useful arts. On this part of the subject I shall have to entrench upon

your patience, and in doing so, I have to invite your earnest and careful attention.

Dr. Ure, in his 'Dictionary of Arts, Manufactures and Mines,' under the article *Evaporation*, observes, "that it is a process by which any substance is converted into and carried off in vapour; further, that the vapour of water is an elastic fluid, whose tension and density depend upon the temperature of water with which it is in contact; that the vapour rising from water, heated to 165° Fahr., possesses an elastic force capable of supporting a column of mercury 108 inches high, and its density is such that 80 cubic feet of such vapour contains one pound of water, whereas 32½ cubic feet of steam, of the density corresponding to a temperature of 212°, and a pressure of 30 inches of mercury, weigh one pound. From this we may calculate, when the temperature of the water is given, the elasticity and specific gravity of the vapour."

In our attempts to vaporize water, or what is technically called, in *raising steam*, we must observe that there is a wide difference between steam generated in an open vessel and steam generated in a close one. In the first case, the temperature never exceeds 212° at the ordinary pressure of the air; whereas in the latter case, the temperature as well as the density and elasticity may be carried to any extent consistent with the safety or strength of the vessel in which it is generated. This is one of the conditions which should never be lost sight of, as the security of life and property not unfrequently depends upon the extent and proper use of our knowledge relative to these properties of steam. It would appear absurd to every thinking person, if I were to attempt to supply data for the construction of vessels calculated to bottle up and retain vaporous matter of highly elastic force, unless I first made myself acquainted with the nature of the material and the agencies I had to deal with; and hence follow the reasons for occupying your time in endeavouring to impart to you such knowledge as I have collected from study and long experience, and which I cheerfully tender for your guidance, as it has served for my own in what I may venture to consider a moderately successful practice.

On the ratio of the temperature, density, and elasticity of steam when in contact with the water that produces it.—The vapours exhaled from a liquid at any temperature contain, according to Dr. Ure, "more heat than the fluid from which they spring, and they cease to form whenever the supply of heat into the liquid is stopped." This is perfectly true; but continue to apply the heat, and also the supply of water—as we find it necessary to do in a furnace and boiler—and we continue the process of evaporation with all its accompaniments of vaporization, firing, feeding, &c., as exhibited in our general practice of raising steam. In conducting with uniformity this process, let us suppose that the temperature of the furnace and the steam, or the evaporated part of the water contained in the boiler, are so adjusted as to be exactly in accordance with the density and quality of the steam produced. We shall then have throughout the whole process the required equivalents of quantities as regards temperature, density, and elasticity.

When steam is confined in the boiler of a steam-engine, fully supplied with water, the heat applied to the boiler raises fresh portions of vapour, which increases the density and elasticity of the steam already formed, so that the increase of temperature, given to the steam, is not only attended with an increase of pressure, but also with an increase of density: experimental tables have been constructed by Arago and Dulong, giving the relation of the elasticity, temperature and density of this steam*. The steam that is thus raised, in contact with its water, is said to be in a state of saturation, or to be saturated with watery vapour, and then the steam has the greatest density it can attain

* The relation of volume and temperature of saturated steam has not yet been determined by direct experiment. In the table referred to, the volume of the steam is calculated on the assumption of the laws of gaseous density, that is to say, on the assumption that the gaseous laws of Mariotte and Gay-Lussac apply to steam in a state of saturation. The calculations of Rankine and Thomson, based upon Carnot's theory and the mechanical equivalent of heat discovered by Joule, show that for temperatures not exceeding 212°, the gaseous laws apply with considerable exactness, but that for higher temperatures there is a decided deviation.

under the given temperature; but if this steam be separated from the water from which it has been formed and additional heat applied, the relations of temperature and density of saturated steam no longer exist, for whilst the temperature of the steam is increased, its density is no longer increased for want of fresh supplies of watery vapour; the steam in this state is said to be anhydrous, that is, in a dry state, and the relations of temperature and pressure, when the steam is allowed to expand, follow a law which has not been as yet exactly determined by experiment. It is important to observe, that the great increase of the elasticity or pressure of steam in a state of saturation, as the temperature is increased, results not merely from the expansive force of the steam already formed, but also from the continual addition of new portions of steam for every addition of temperature: the additions of heat are not expended in simply tending to expand the steam, but also in adding fresh portions of steam to that which is already formed, and thereby increasing its density as well as its elasticity.

I would earnestly call your attention to these facts, for many of the most serious boiler explosions have arisen from a want of a proper appreciation of them. For further information on this subject, see the "Researches into causes of the explosions of a Locomotive Engine at Longsight," Appendix No. II., in which will be found a series of experiments bearing directly on the generative powers of the steam-boiler.

It has been shown by different experimentalists, that the following gaseous laws hold true, or at least nearly true, in relation to steam:—

1. The pressure of steam is inversely as its volume when the temperature remains the same. This is known by the name of Mariotte's or Boyle's law.

Thus let V represent the volume of a given weight of steam, P its elastic pressure; and let V_1 represent the volume of the same weight of steam at the pressure P_1; then supposing the temperature of the steam to be the same in both cases, we have

$$\frac{P}{P_1}=\frac{V_1}{V} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (1)$$

According to this law, if a given weight of an elastic fluid be compressed to half its primitive volume, without changing its temperature, the elastic force of that fluid will become double.

2. All elastic fluids, under the same pressure, expand uniformly for equal increments of temperature.

The expansion of a given volume of an elastic fluid at 32° is $\frac{1}{490}$th part of this volume for every degree of temperature. This law was discovered by Gay-Lussac and Dalton.

If V and t be put for the volume and temperature of a given weight of an elastic fluid, and V_1 the volume of the same weight of fluid when the temperature is t_1, the pressure remaining the same; then it follows from this law, that

$$\frac{V}{V_1}=\frac{458+t}{458+t}. \quad \quad (2)$$

Moreover, if P be put for the pressure at the volume V, and P_1 the pressure at the temperature t_1, supposing the volume of the fluid to remain unchanged, then

$$\frac{P}{P_1}=\frac{458+t}{458+t_1}. \quad \quad (3)$$

When the volume as well as the temperature of the elastic fluid is changed, we find, from a combination of the two gaseous laws, the following relation:

$$\frac{V \times P}{V_1 \times P_1}=\frac{458+t}{458+t_1}. \quad \quad (4)$$

In the case of steam, if $t_1=212°$, $P_1=15$, and $V_1=1670$, which is the volume of steam raised from a unit of water at this temperature and pressure, then this expression becomes

$$V=\frac{1670 \times 15}{670} \times \frac{458+t}{P},$$

which gives the volume of steam at P pressure, and t temperature raised from a unit of water. The Tables giving the temperature, pressure and volume of steam are calculated by this formula. For example, if $t=330°$, and $P=100$ lbs. as determined by experiment, then

$$V=\frac{1670 \times 15}{670} \times \frac{458+330}{100}=294 \text{ nearly},$$

which is the volume of a unit of water in the form of saturated steam at 330° temperature, and 100 lbs. pressure per square inch*.

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* The valuable experiments of Regnault show that the laws of Mariotte and Gay-Lussac are very nearly strictly true as applied to permanently elastic fluids. The deviations from the law of Mariotte are so small that they may almost be taken as errors resulting from observation. According to Regnault's experiments, the coefficient of expansion of air for every degree Cent. above the freezing-point of water is ·003665, or $\cdot 002036 = \frac{1}{491}$ nearly, for every degree Fahr. This coefficient has been deduced from the change of elastic force which the same volume of gas undergoes when its temperature changes 1°. But the number ·003667, or $\cdot 002037 = \frac{1}{490 \cdot 8}$ nearly, should be adopted when the gas is allowed to expand freely under the same pressure. Regnault further determined that the coefficient of expansion varies with the density of the gas: his results are given in the following Table:—

Table of dilatation of air at different densities.

Density of the air at 0° Cent., the mean density of the atmosphere being unity. p.	Coefficient of expansion for every degree Cent. θ.
0·1444	·0036482
0·2294	·0036513
0·3501	·0036542
0·4930	·0036587
1·0000	·0036650
2·2084	·0036760
2·2270	·0036800
2·8213	·0036894
4·8100	·0037091

If θ be put for the coefficient of dilatation at p density, then the following formula will give an approximate expression for the values contained in this table:—

$$\theta = \cdot 003665 + \cdot 000018\,(p-1) - \cdot 0000018\,(p-1)^2 \;\ldots\ldots\ldots (1)$$

If V and t be put for the volume and temperature of a given weight of air at p pressure, having the corresponding coefficient of expansion θ, and V_1 the volume of the same weight of fluid when the temperature is t_1, the pressure remaining the same; then it follows from this law that

$$\frac{V}{V_1} = \frac{1+\theta t}{1+\theta t_1} \;\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (2)$$

Similarly, we have for the same weight of air, when the coefficient of

On the total quantity of heat in steam at different temperatures.—According to the experiments of Regnault, the total amount of caloric in steam at 212°, or boiling-point, is 1146°·6 Fahr., that is to say, the heat necessary to form a pound-weight of steam at

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expansion corresponding to the pressure p' is θ', the volumes at t and t_1 temperatures being V' and V_1' respectively,—

$$\frac{V'}{V_1'}=\frac{1+\theta' t}{1+\theta' t_1}. \qquad (3)$$

From (2) and (3) we get

$$\frac{V}{V'}=\frac{V_1}{V_1'}\times\frac{(1+\theta t)\,(1+\theta' t_1)}{(1+\theta t_1)\,(1+\theta' t)} \qquad (4)$$

Here $\frac{V}{V'}$ is the ratio of the volumes of the same weight of air at the same temperature t, at the different pressures p and p'; and in like manner $\frac{V_1}{V_1'}$ is the ratio of the volumes of the air at the same temperature t_1, at the different pressures p and p'. This expression shows that these ratios are not equal, for when p' is greater tham p, then θ' is greater than θ. Hence we derive the following remarkable result:—

If the law of Mariotte be strictly true for any given temperature t, *it will not be strictly true for any other temperature* t_1.

According to the law of Mariotte, let

$$\frac{\frac{V}{V'}}{\frac{p'}{p}}=\frac{V}{V'}\cdot\frac{p}{p'}=1\,;$$

but when the temperature is t_1, by equation (4) this expression becomes

$$\frac{V_1}{V_1'}\times\frac{(1+\theta t)\,(1+\theta' t_1)}{(1+\theta t_1)\,(1+\theta' t)}\times\frac{p}{p'}=1\,;$$

$$\therefore\ \frac{V_1}{V_1'}\cdot\frac{p}{p'}=\frac{\frac{V_1}{V_1'}}{\frac{p'}{p}}=\frac{(1+\theta t_1)\,(1+\theta' t)}{(1+\theta t)\,(1+\theta' t_1)}=1+\frac{(t-t_1)\,(\theta'-\theta)}{(1+\theta' t_1)\,(1+\theta t)} \qquad (5)$$

If p' be greater than p, then θ' is greater than θ: and for all values of t_1 less than t, this fraction will be greater than unity, and for all values of t_1 greater than t, it will be less than unity: hence if the law be true for the temperature t, it will not hold strictly true for the temperature t_1. But the excess or deficiency $\frac{(t-t_1)\,(\theta'-\theta)}{(1+\theta' t_1)\,(1+\theta t)}$ will, in all possible cases, be a small fraction. For example, let p be equal to the atmospheric pressure, $p'=3p$,

212° temperature (supposing the water in the boiler to be at first 32°), would raise the temperature of a pound of water (supposing it to remain liquid) 1146°·6, or, what is the same thing, it would raise the temperature of 1146·6 lbs. of water 1°. It will be convenient to adopt some unit of caloric; for this purpose we shall define a unit of caloric to be that amount of heat which is necessary to elevate a pound of water 1°; according to this definition, the total number of units of caloric in a pound of steam at 212° is 1146·6, and the number of units of latent caloric in it will be 1146·6 less by 212, or 934·6.

Dr. Black, the discoverer of latent heat, concluded from his experiments, that the sum of the sensible and latent heat of a given weight of steam is always the same, or in other words, that a given weight of steam at any given pressure contains the same amount of caloric that there is contained in the same weight of steam at any other pressure. This simple law, until very recently, was universally adopted by natural philosophers; but the experiments of Regnault have shown that the total amount of caloric in a given weight of steam increases (slowly) with the increase of temperature. If we take the total units of caloric of steam at 212° to be 1146·6, and if λ be put for the total units of caloric at T temperature, then—

The law of Black will be expressed by

$$\lambda + T = 1146{\cdot}6, \text{ or } \lambda = 1146{\cdot}6 - T.$$

And the law discovered by Regnault will be expressed by

$$\lambda = 1082 + {\cdot}305T \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (5)$$

At 212° sensible temperature, the total caloric in both cases

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$t=100°$, $t_1=0$, then by formula (1) we find $\theta={\cdot}003665$, and $\theta'={\cdot}00369$; hence we find by substituting in formula (5)

$$\frac{\dfrac{V_1}{V_1'}}{\dfrac{p'}{p}} = 1 + \frac{100 \times {\cdot}000025}{1 + {\cdot}3665} = 1{\cdot}002 \text{ nearly.}$$

This will, to a certain extent, account for the discrepancies which have been observed by different experimentalists.

will be 1146°·6; whereas at 300° the total caloric according to Regnault's law will be 1173°·5, which is about 27° in excess of 1146°·6, and, on the contrary, at 190° the total caloric according to Regnault's law will be 1140 nearly, which is about 6° less than 1146°·6. Now taking 16·4 as the mean of these differences, and adding it to 1146·6, we shall have $\lambda=1163$ as a mean value for the total caloric of steam, according to Black's law, which will not differ much from the true value as derived from Regnault's formula for different temperatures.

The formula $\lambda=1082+\cdot305T$ is of great significance and importance. It shows that in order to raise the temperature of saturated steam 1°, there must be ·305 of a unit of caloric added to that steam*. It is therefore apparent that steam of a high pressure contains more caloric than steam at a less temperature, and therefore it is most economical to evaporate liquids at as low a temperature as possible.

The following table† exhibits the total caloric contained

* This fraction may be regarded as the specific heat requisite for maintaining the steam in a state of saturation. No direct reliable experiments have yet been made for the determination of the specific heat of steam at constant volume, or at constant pressure. The specific heat of air has been determined with considerable precision. The specific heat of air at constant volume=0·17 nearly, and at constant pressure =0·24 nearly. The ratio of these numbers, k, is 1·41, which is usually taken as constant for all pressures and temperatures.

† The relation of the elements contained in this table are expressed with great precision by the following general formulæ:—

$$\log p=\frac{5\cdot083\ (\lambda-1146\cdot6)}{\lambda-967} \quad \ldots\ldots\ldots\ldots\ldots\ldots (1)$$

$$\log p=\frac{5\cdot083\ (T-212)}{T+377} \quad \ldots\ldots\ldots\ldots\ldots\ldots (2)$$

For T=122°, 212° and 302°, the values of p derived from these formulæ exactly agree with the values given in the table. For T=392°, the values of p derived from the formulæ are only $\frac{1}{150}$th part in excess of the values of p given in the table, and for T=32° the values of p derived from the formulæ are $\frac{1}{30}$th in deficiency.

The constants in these formulæ have a certain relation to each other. The constant 5·083 is the same in both formulæ. The constant 1146·6 in formula (1) is the total caloric λ, corresponding to the temperature T, indicated by

in steam at different temperatures raised from a unit of water at 32°:—

Temperature of the vapour. T.	Pressure of the vapour in atmospheres. p.	Total caloric. λ.
32°	0·006	1091·70
50	0·012	1097·20
68	0·023	1102·70
86	0·042	1108·19
104	0·072	1113·68
122	0·121	1119·17
140	0·196	1124·66
158	0·306	1130·15
176	0·466	1135·64
194	0·691	1141·13
212	1·000	1146·62
230	1·415	1152·11
248	1·962	1157·60
266	2·671	1163·09
284	3·576	1168·58
302	4·712	1174·07
320	6·120	1179·56
338	7·844	1185·05
356	9·929	1190·54
374	12·425	1196·03
392	15·380	1201·52
410	18·848	1207·01
428	22·882	1212·50
446	27·535	1217·99

Let us now inquire what takes place when saturated steam, separated from the water, is allowed to expand or to contract.

According to Black's law, the steam will always remain in a state of saturation, whether it be compressed or expanded; for,

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the constant 212 of formula (2); and in like manner the constant 967 of formula (1) is the value of λ corresponding to the temperature $T=-377$, indicated by the constant 377 of formula (2). So that the constants of total caloric in the one formula correspond to the constants of temperature in the other.

When $T=-377°$, $\log p=-\infty$, that is $p=0$; this seems to show, that at the temperature of 377° below zero (Fahr.), the pressure of the vapour of water is nothing. We might reasonably expect that there should be a limit to the repulsion of the particles of vapour to each other; this limit should take place at that point of temperature where the repulsive force of the heat is balanced by the cohesive attraction of the particles of the vapour. The

according to this law, the total caloric in steam at all pressures is the same, and consequently the contraction or expansion of the steam could not change the capacity of the steam for watery vapour. It is on this assumption that the work of steam, acting expansively in the cylinder of the steam-engine, is usually calculated; but according to Regnault's law, this work will be slightly in deficiency. At the same time it must be observed, that owing to the condensation of steam which must necessarily take place in the cylinder at the commencement of every stroke of the piston, a sufficient quantity of water must always be

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result derived from formula (2) seems to indicate that this temperature is at 377° below zero.

When $T=\infty$, $\log p=5{\cdot}083$, and $p=121200$ atmospheres, which is the maximum value of p derived from the formula.

From formula (1) we get

$$\lambda=967+\frac{913}{5{\cdot}083-\log p}\text{. }\ldots\ldots\ldots\ldots\ldots\ldots\ldots (3)$$

And from formula (2),—

$$T=\frac{2993{\cdot}9}{5{\cdot}083-\log p}-377.\ldots\ldots\ldots\ldots\ldots\ldots\ldots (4)$$

Formulæ (1) and (2) may be reduced to the following forms :—

$$\log p=5{\cdot}083-\frac{913}{\lambda-967}\text{. }\ldots\ldots\ldots\ldots\ldots\ldots (5)$$

$$\log p=5{\cdot}083-\frac{2993.9}{T+377}\text{. }\ldots\ldots\ldots\ldots\ldots\ldots (6)$$

Again, putting $\log a=5{\cdot}083$, $\log k=913$, and $\log k'=2993{\cdot}9$, these formulæ become

$$k^{\frac{1}{\lambda-967}}\times p=a \ \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (7)$$

$$k'^{\frac{1}{T+377}}\times p=a.\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (8)$$

The formula, $\lambda=1082+{\cdot}305\,T$, expresses the total quantity of caloric which must be communicated to a unit of water at 32° to maintain it in the form of steam at T temperature. Now let t be the temperature of the water in the boiler before heat is applied, and Q be put for the units of caloric requisite for raising this water in the form of steam at T temperature; then as this water will contain $t-32$ units of caloric before the heat is applied, we shall have

$$Q=1082+{\cdot}305T-(t-32)\,;$$
$$\therefore\ Q=1114+{\cdot}305T-t.$$

present in the cylinder to saturate the steam with vapour as it expands in the cylinder; it therefore follows that the steam in the cylinder of an expansive engine will always be in, or at least very nearly in, a state of saturation.

According to Regnault's law, steam at a high pressure contains more caloric than steam at a less pressure: hence it follows that when saturated steam is compressed, a portion of watery vapour is precipitated; and, on the contrary, when saturated steam is allowed to expand, it becomes anhydrous, that is to say, it no longer contains all the watery vapour which it is capable of supporting. For example, if a pound of steam at 15 lbs. pressure be compressed until it has a pressure of 100 lbs., there will be about ·029 lb. of water precipitated.

There is a great advantage gained by using steam of high pressure; for whilst the work performed by steam is nearly in proportion to its pressure, the quantity of heat contained in steam of high pressure is very little more than that which is contained in steam of low pressure. Thus, for example, the number of units of heat contained in a pound of steam at 100 lbs. pressure or 330° temperature, is only $\frac{1}{55}$th part more than the units of heat contained in a pound of steam at 35 lbs. pressure or 260° temperature*.

Attempts have been made to increase the efficiency of the steam-engine by employing what is called "surcharged steam," or steam that has been heated after it has left the boiler. The advantage which is supposed to be derived from this plan is, that anhydrous or dry steam has a less capacity for heat than saturated steam, whose temperature is raised whilst in contact with water. The leading features of this plan may be described as follows:—

Let A represent a steam-boiler of the usual construction, *s* the

* This calculation is performed in the following manner:—

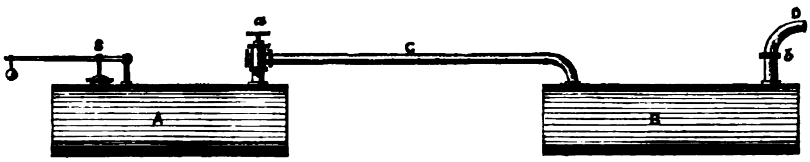
Units of heat at 330°, or $\lambda = 1082 + \cdot 305 \times 330 = 1182$;

Units of heat at 260°, or $\lambda_1 = 1082 + \cdot 305 \times 260 = 1161$;

$$\therefore \frac{\lambda}{\lambda_1} = \frac{1182}{1161} = 1\tfrac{1}{55} \text{ nearly.}$$

safety-valve, *a* a stop-cock, C a pipe conveying the steam into a large receiver B, which is heated by means of a furnace, *b*D a pipe conducting the heated steam to the cylinder of an ordinary steam-engine. The steam from the boiler A time after time fills

Fig. 10.



the receiver B, where its temperature is raised until it attains a considerable working pressure; in this state it then flows into the cylinder, where it performs work by its expansion, as in an ordinary steam-engine.

Let us suppose the receiver B to be filled with steam at 212°, raised from a cubic foot of water, and let this steam be heated, say to the temperature of 294°, then it will expand precisely as air or any other gas, and the increase of elasticity, according to Gay-Lussac's law, will be from 1 atmosphere to $1\frac{1}{8}$ atmosphere, that is, from a pressure of 15 lbs. per square inch to about 17 lbs. per square inch*; but when this steam is heated to 294° in contact with water, the additional application of heat increases the density of the steam so that it attains a pressure of 4 atmospheres, that is, a pressure of 60 lbs. per square inch. Now it scarcely requires any calculation to show that the work of steam raised from a cubic foot of water at 60 lbs. pressure must be very much greater than the work of the same weight of steam at 17 lbs. pressure; in fact, that the work in the former is nearly five times the work in the latter; but according to Regnault's law (see formula (5)), the cubic foot of water in the form of saturated steam at 294° contains only about $\frac{1}{60}$th part more total caloric than the cubic foot of water in the form of steam at 212°; hence it appears, that with less than $\frac{1}{60}$th more

* By formula (3), $P = P_1 \times \frac{458+t}{458+t_1} = 15 \times \frac{458+294}{458+212} = 17$ lbs. nearly.

caloric we have about five times the work. From this it is obvious that the employment of surcharged steam, in *this manner*, is not so economical as the way in which steam is now employed. It is true, that by applying an enormous heat to the receiver B, the work of the anhydrous or heated steam may be very much increased. But in order to have a fair comparison between the two methods, we should have the saturated steam heated to the same temperature as the anhydrous steam. No doubt some advantage may be gained by heating the steam in the receiver until it attains a pressure equal to, or nearly equal to, the pressure of the steam usually employed in our steam-engines, but in most cases this would require the application of a destructive temperature. It would require the steam at 212° to be raised in the receiver to a temperature which would fuse copper in order to give that steam a pressure of 60 lbs. per square inch*.

* I purpose to make (in a few months' time) a series of experiments with the view of determining whether or not any real advantage is gained by the use of surcharged steam, beyond that of preventing condensation and the loss of heat.

LECTURE VIII.

ON STEAM.

In the preceding Lecture we endeavoured to show, by a series of investigations,—

1st. That in working a steam-engine, it is most convenient to employ steam in the usual manner, when the temperature of the steam in the cylinder is the same as the temperature of the heated steam in the receiver or pipe communicating with the boiler.

2nd. That an advantage may be gained by the use of heated steam, when the temperature of the steam in the receiver is elevated above the temperature of the saturated steam in the cylinder.

The truth of these conclusions will, however, depend upon the value of the constants of specific heat; and before we can arrive at definite results on a question of such importance as that which involves the comparative efficiency of surcharged steam, it will be necessary to determine, by actual experiment, the exact value of the specific heat of steam under constant volume, as well as under constant pressure.

These experiments, if carefully conducted, would solve the difficulty which at present exists, and probably determine the exact law which marks the difference between heat when applied to steam under constant density and volume, and steam under circumstances where the volume is constant, but the density increased. At some future period we shall have to consider both these questions; for the present we must content ourselves with an inquiry,—

1st. Into the relative force of steam at different temperatures;

2nd. Into the relative volume of steam to its equivalent volume of water; and

Lastly, Into the laws which govern the mechanical action of steam, loss of temperature, &c. To all these subjects, bearing directly upon the use and appliances of steam, I invite your attention: and I trust, that what I have to communicate to you on these subjects will contribute to the extension of your knowledge in this department of practical science.

1. *On the relative Force of Steam at different Temperatures.*

The discoveries and experimental researches of Dalton exhibit some curious and interesting facts. In his Essays "On the Constitution of mixed Gases, or the Force of Steam or Vapour from Water and other Liquids at different Temperatures," "On Evaporation and the Expansion of Gases by Heat," &c., he states, when treating of these different subjects,—

"1st. When two elastic fluids, denoted by A and B, are mixed together, there is no mutual repulsion amongst the particles; that is, the particles of A do not repel the particles of B, as they do one another. Consequently, the pressure or whole weight upon any one particle arises solely from one of its own kind.

"2nd. The force of steam from all liquids is the same, at equal distances above and below their several temperatures at which they boil in the open air, and that force is the same under any pressure of any other elastic fluid as it is *in vacuo.* Thus the force of aqueous vapour at 212° is equal to 30 inches of mercury; at 30° below, or 182°, it is of half that force; and at 40° above, or 252°, it is of double the force. So likewise the vapour from sulphuric ether which boils at 102°, then supporting 30 inches of mercury, at 30° below that temperature, is of half the force, and at 40° above it, is of double the force, and so on in other liquids.

"3rd. The quantity of any liquid evaporated in the open air is directly as the force of steam from such liquid at its temperature, all other circumstances being the same.

"4th. All elastic fluids expand the same quantity by heat; and this expansion is very nearly in the same equable way as that of mercury, at least from 32° to 212°."

From these extracts it would appear that the expansion of all elastic fluids, whether from water or any other liquid, follows the same law, and that the expansion of the particles of the same fluid will be directly as the increase of temperature.

On this question of temperature and elastic force Dalton has made some exceedingly simple as well as conclusive experiments, which he has tabulated, showing the force of vapour from water at every temperature—from that of the congelation of mercury, or 40° below zero, to 325° of Fahrenheit. In this Table he gives the force of the vapour in numbers corresponding to the temperature as follows:—

Temp.	Force of vapour, in in. of mercury.	Pressure in lbs. per square in.	Temp.	Force of vapour, in in. of mercury.	Pressure in lbs. per square in.
°			°		
—40	·013	·006	80	1·00	·500
—20	·030	·015	100	1·86	·930
—10	·043	·021	150	7·42	3·710
0	... .	...	212	30·00	15·000
10	·090	·045	250	58·21	29·105
20	·129	·064	300	111·81	55·905
40	·263	·131	325	140·70	70·700
60	·524	·262			

Now if we compare the above deductions with actual experiments upon a large scale, as deduced from my own experiments and those of Arago and Dulong, it will be found that up to 250° there is a remarkable degree of correspondence, but above this temperature Dalton's ratio of pressure and temperature differs considerably, the pressures being below those of Arago, Dulong, and my own. At 300° and 325°, for example, he gives the pressure or force at 55·9 and 70·7 lbs. on the square inch, whereas in my own experiments the pressures at the same temperatures are respectively 72 and 106 lbs., and in those of Arago and Dulong they are 66 and 94 lbs. In my own experiments, as derived from the locomotive engine at Longsight, they differ at the higher temperatures from both Dalton and Dulong, as may be seen by the following numbers, which

indicate the force of the steam at the respective temperatures of 250°, 300°, and 325°.

COMPARATIVE FORCE OF STEAM at different temperatures, as derived from the experiments of Dalton, Arago, Dulong, &c.

Temperature.	Dalton.	Fairbairn.	Arago and Dulong.
250°	29·0	30·2	29·5
300	55·9	72·7	66·0
325	70·7	106·8	94·0

From this it is obvious that the pressures per square inch have a remarkable coincidence up to 250°; above that temperature they do not agree, Dalton's results being as much below as mine are above Arago's and Dulong's*.

It is probably difficult to account for the discrepancies which present themselves in these experiments: they may arise from different causes; in the case of Dalton, from not having means and opportunity to conduct his experiment on a large scale; and Arago and Dulong, although supplied with appropriate apparatus and every convenience that a government can afford, might nevertheless encounter difficulties which the present construction of steam-engines adapted to work at high pressures has a tendency to remove. Besides, it is not improbable that the application and the difference of instruments used in ascertaining the temperature, may have been such as to account in some measure for the discrepancies which occur; and this is the more strikingly apparent, when the results obtained from the higher temperatures and pressures of Arago and Dulong are considered in reference to those indicated by the experiments at Longsight†. To these differences we may at some future time have occasion to refer; but this question can only be settled by renewed experiment and research; and in doing so, we shall endeavour either to account for the discrepancies which exist, or to confirm the results of the experiments which were

* The experiments of Regnault (see page 157) give 30·5, 68·7, and 98·6 nearly for these pressures.

† The air-thermometer is probably the most trustworthy instrument in conducting these experiments.

made on the occasion referred to above. For the present we proceed to the consideration of the next division of our subject.

2. *The relative volume and density of Steam to its equivalent volume of water.*

Numerous experiments have been made to ascertain the relative temperatures and densities of steam, but they have seldom been extended beyond a few atmospheres; most of them, in fact, have been made below the pressure of the atmosphere, which, taken as a scientific inquiry, is highly valuable; but to the practical engineer (having to deal with steam as high as six or seven atmospheres, and when he may be called upon at some future time, as our theoretical and practical knowledge extends, to use and economize steam at double that pressure) they are comparatively of little value. It is true, we have the experiments of Arago and Dulong, as given by the Academy of Sciences, and those of Pambour in the treatise referred to in the last Lecture; but even those experiments, surrounded as they are by technical formulæ, are not of a character to instruct the operative engineer in the elementary truths connected with his professional pursuits. The experiments of Arago and Dulong were undertaken for a scientific as well as a practical object; they were instituted at the request of the Academy of Sciences of the Institute of France, almost exclusively for the purpose of determining certain laws; and as no expense was spared, they were conducted with great exactitude, and now form important data, which may safely be referred to, on the elastic power of steam at moderately high temperatures*.

* In the pursuit of experimental research, I would here notice the difference which exists between the Government of France and that of our own country. Whenever a doubtful question in science has to be determined by experiment, the Government cheerfully undertakes it, generally through the medium of the National Institute. In this country, the Government in general leaves the inquiry (frequently attended with great expense) to individuals. I will not say what I have myself spent in this way, but I am glad to observe a more liberal and generous feeling on the part of Her Majesty's Government in the yearly grant of £1000, obtained through the medium and interest of Lord John Russell, as an encouragement for the promotion and extension of science.

Finding the experiments of Arago and Dulong limited in their application as respects temperature and pressure, I availed myself of an accident which occurred a few years since, by the explosion of a locomotive engine at Longsight, near Manchester, to extend these inquiries; and conceiving that the experiments then made refer with peculiar force to the present inquiry, I am sure you will not think me tedious if I attempt to introduce them on the present occasion. They will be found of considerable value and importance, when compared with those of Arago and Dulong; and having extended them as high as the thermometers ranged (upwards of seven atmospheres), I trust they will not be the less acceptable for their approximate agree-

TABLE of Temperatures, &c.

Pressure in pounds per square inch.		Corresponding temperature by Fahrenheit.	Relative volume of steam compared to volume of water that produced it.	Pressure in pounds per square inch.		Corresponding temperature by Fahrenheit.	Relative volume of steam compared to volume of water that produced it.
Below the atmosphere	1	102°·9	20954	Above the atmosphere	24	266°·9	693
	5	161·4	4624		26	269·9	662
	10	192·4	2427		28	272·9	634
	15	213·0	1669		30	275·7	608
Above the atmosphere	1	216·4	1572		35	282·3	552
	2	219·6	1487		40	288·4	506
	3	222·6	1410		45	294·1	467
	4	225·6	1342		50	299·1	434
	5	228·3	1280		55	304·2	406
	6	231·0	1224		60	308·9	381
	7	233·6	1172		65	313·5	359
	8	236·1	1125		70	317·8	340
	9	238·4	1082		75	321·9	323
	10	240·7	1042		80	325·8	307
	11	243·0	1005		85	329·6	293
	12	245·1	971		90	332·2	281
	13	247·2	939		105	343·3	249
	14	249·2	909		120	352·4	224
	15	251·2	882		135	360·8	203
	16	253·1	855		150	368·5	187
	17	255·0	831		165	375·6	173
	18	256·8	808		180	382·3	161
	19	258·6	786		195	388·6	150
	20	260·3	765		210	394·6	141
	22	263·7	727		225	400·2	133

ment with the experiments of the distinguished philosophers referred to*.

Treating of the volume of steam generated under different pressures compared with the volume of water which produced it, Pambour has compiled a Table from calculations founded on the experiments of Arago and Dulong, of which the foregoing table, with certain alterations in the arrangement, is an extract.

I have given this abstract in the tabulated form in order to admit of comparison with the results of the actual experiments, made at Longsight for the purpose of ascertaining the rate at which steam accumulates, and also for determining its corresponding rate of increase of pressure with the fire under the boiler, all the outlets for the escape of the steam being closed. Mr. Ramsbottom, the Resident Engineer on the North-Eastern Division of the London and North-Western Railway, kindly undertook such experiments as were calculated to ascertain the rate of accumulation of pressure in a locomotive engine having no escape for the steam, and its safety-valves made fast; but as those experiments, although perfectly satisfactory, were limited in their extent, I deemed it necessary to repeat them under the ordinary circumstances of the engine standing, and as nearly as possible in the same condition with the fire under the boiler as that which exploded.

Mr. Ramsbottom conducted his experiments from 30 lbs. up to 80 lbs. on the square inch; but in order to ascertain more distinctly the rate of increase in the pressure, it was considered desirable to extend them through a greater range of temperature, and to prove that we could not with impunity for any length of time continue to shut off all means of escape for the steam, with a blazing or even a moderate fire under the boiler. From these experiments the following results were obtained:—

* For an account of these experiments, see Appendix, No. II.

EXPERIMENTS made to determine the rate of increased pressure, temperature of steam, &c., in a locomotive engine with the safety-valve screwed down and the fire under the boiler*.

Time.	Pressure in lbs. per square inch above the atmosphere.	Temperature. No. 1 Gauge.	Temperature. No. 2 Gauge.	Mean Temperature.
h m				
2 44	11·75	243°	243°	243°·00
2 45	14·15	247	247½	246·75
2 46	16·35	251	251	251·00
2 47	19·25	255½	255	255·25
2 48	22·35	260	259½	259·75
2 49	25·75	264	264	264·00
2 50	28·95	268½	268¼	268·37
2 51	32·15	273	273	273·00
2 52	35·75	277	277	277·00
2 53	39·95	282	282	282·00
2 54	44·25	286½	286¼	286·37
2 55	48·35	291	291	291·00
2 56	52·75	295½	295¼	295·37
2 57	57·75	300	300	300·00
2 58	63·75	304¼	304¼	304·25
2 59	68·95	308½	309	308·75
3 00	74·75	313	313	313·00
3 1	80·35	318	317½	317·75
3 2	87·25	322	322	322·00
3 3	93·95	326¼	326	326·12
3 4	101·15	331	331	331·00
3 5	108·75	335½	335¼	335·37
3 6	111·75	This experiment was lost, the thermometers not indicating a higher temperature.		

On comparing the computed Table of Pambour on pressure and temperatures with the above results, no great difference will be found to exist, excepting only at the higher pressures, where the difference is only about 2¼ per cent. We may therefore consider them as near an approximation as the state of the thermometers and circumstances would admit.

It will be observed, from the extracts thus given from my own experiments, and the comparison made between them and those of Arago and Dulong, that the results are not widely

* On comparing this Table with the experiments of Dalton, Arago, and Dulong, it will be found that the elastic force of the steam is calculated by those philosophers from temperatures below the boiling-point of water, whereas the above commences at 31° above that point, or 243° of Fahrenheit. For particulars, see Appendix, No. II.

different. On the contrary, they approximate closely to each other; and the tables themselves correspond so nearly to the truth, that we may safely recommend them for adoption in every case where the temperature, density, and volume of steam become questions of consideration for the practical engineer*.

In speaking of a volume of steam, as compared to the volume of water that produces it, we must bear in mind that it has been ascertained that steam generated under the pressure of the atmosphere (15 lbs. on the square inch) will occupy, in round numbers, 1700 times that of the water from which it is generated.

Pambour and others have given formulæ for calculating the volumes of steam raised from a unit of water at different pressures; but wishing to avoid theoretic deductions, we shall content ourselves by showing in the annexed diagram the volume which steam at different pressures occupies in relation to its volume of water.

In this comparison I have endeavoured to trace the relative bulk or volume of the atoms of steam to their corresponding volumes of water; and on looking over the diagram, it will be observed that the atoms of water, when thus expanded by heat, harmonize in consecutive order with their respective pressures; and that each atom of water, when converted into steam, will occupy the particular space to which its volume is entitled by the expansive force of heat. This beautiful law of nature gives us the use and the control of an elastic force, which, if directed with prudence, may yet confer benefits unheard-of in the past history of physical science.

We have already stated that Pambour, in his discussions on the relative volume of steam and the pressure at equal temperatures, remarks, "that if the volume of any weight of gas or of steam be made to vary without changing its temperature, the elastic force of the gas will vary in the inverse ratio of the volume it is made to occupy:" or, in other words, again

* I have taken the relative volume of steam, as compared to that of water, from the researches of Boyle, Gay-Lussac, Arago, &c.

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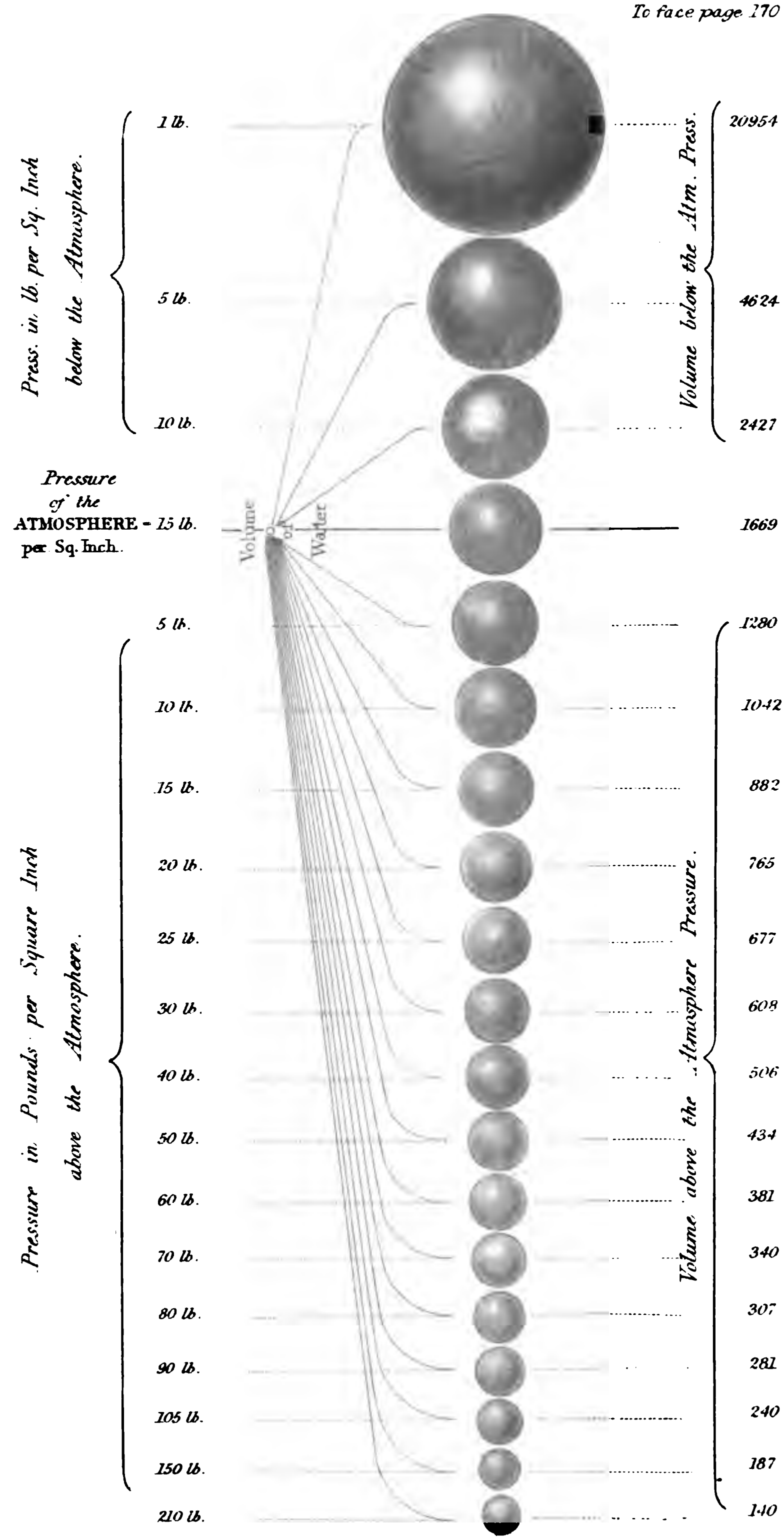


quoting from his 'Practical Treatise,' "that, according to this law, if a given weight of an elastic fluid be compressed to half its primitive volume, without changing its temperature, the elastic force of that fluid will become double. But it is plain that this effect cannot take place in the steam in contact with the liquid, because it is supposed that during the change of pressure the temperature remains constant, whereas we have seen that in such a state the pressure always accompanies the temperature, and *vice versâ*."

Now, on this subject it has been shown that we cannot increase the density of bodies without increasing at the same time the temperature; and this is strongly exemplified in some interesting experiments on densities with which I am at present engaged. It appears to be a universal law, that any increase of pressure is followed by its relative increase of temperature, and that we cannot with impunity attempt to force the atoms or molecules of bodies into closer contact without an equivalent increase of temperature. This appears to be a fixed and determined principle of nature, which I have found amply verified up to a pressure of 6000 atmospheres or 90,000 lbs. on the square inch. These curious and exceedingly interesting experiments are far from being completed, and it would probably be ill-timed to trouble you with them at present; I may, however, observe that M. de Pambour notices some properties in the effects of steam discovered by the celebrated chemist M. Gay-Lussac, which to some extent bear upon the questions of temperature and pressure. They are as follows:—"That if the temperature of a given weight of an elastic fluid be made to vary, its tension being maintained at the same degree, it will receive augmentations of volume exactly proportional to the augmentation of temperature, and according to the latest experiments, for each degree of the Centigrade thermometer the increase of volume will be ·00366 of the volume which the same weight of fluid occupies at the temperature zero."

Reducing the Centigrade thermometer to that of Fahrenheit, we should then have for each augmentation of 1° of temperature

an increase of ·00203 of the volume occupied by the fluid at the temperature of the foregoing point, or 32°. This law does not however apply to steam in contact with the water, as the density in this case invariably increases with the temperature, and *vice versâ*, as we have already demonstrated by the experiments referred to.

3. *On the Laws which govern the Mechanical Action of Steam, Loss of Temperature, &c.*

There exists a difference of opinion on this point amongst philosophers, particularly as regards the properties of steam in contact with the water in the boiler. It is well known that steam, when evaporated from water under the pressure of the atmosphere, never exceeds a temperature of 212° Fahr., and that whatever quantity of heat be added to the water, it never rises above that temperature. I may again observe, that all the heat given out by the furnace to the water must be absorbed by the steam, and must remain in it in a latent state, which is evidently the case, as the additional increments of heat have no effect on the thermometer, and only become perceptible when the steam is condensed, that is, by depriving it of its latent heat. Pambour considers the latent heat of steam to be such as to maintain the particles of water in the degree of separation suitable to the new state of the elastic fluid, and to become absorbed by the steam in a manner similar to that in which it is absorbed by the water in passing from the state of ice to that of liquefaction.

It is however important to know the changes and modifications steam may undergo when separated from the water, and conveyed, as is almost invariably the case, from the boiler to the engine, where its mechanical effect is tested by the force with which it impinges upon the piston of that highly important and useful machine.

Now, as the latent heat of steam has something to do with this process, I am sure you will pardon me if I endeavour to give you as clear a conception as possible of what we have to

guard against in the escape of heat under circumstances where loss of density and temperature is the result.

The transport or conveyance of steam to any distance is invariably attended with loss from the escape or radiation of heat from the pipes by which the steam is conducted in its passage to the engine, or to the spot where it has to be used, either as an element of motive power, or for the purposes of heating, boiling, &c. Deprived of a portion of its caloric, it then becomes steam of a different description to what it was when in contact with the liquid in the boiler, and where it was receiving constant supplies of heat from the furnace. Once admitted into the pipes, that contact with the fluid, so essential to the maintenance of its temperature and density, no longer exists; and unless we are very careful, a considerable portion of its heat and pressure will inevitably escape. This is a question of deep importance to every one engaged in the generation and application of steam, and I cannot sufficiently impress upon the minds of the operative as well as the professional engineer, the necessity which exists for instituting a careful inspection into all circumstances connected with the clothing of pipes and boilers, to prevent the escape or disengagement of that subtle fluid, heat. Under all circumstances, we should therefore pay special attention to the retention of heat, whether latent or otherwise, in the steam, by carefully clothing the exterior surfaces of pipes and boilers exposed to the atmosphere.

Having thus far directed your attention to the various conditions of water in the solid, fluid and gaseous states, it now only remains for me to trespass upon your time a little longer, whilst I endeavour to show in what manner the steam thus generated and thus conveyed can best be employed to produce mechanical effect, with the greatest economy in all the varied forms of its application.

In the preceding observations I have urged upon you the necessity of using every precaution to preserve the heat (whether latent or active) in the steam, and in its transport to the locality

of application. Heat is one of those insidious agents that is constantly on the watch to make its escape. It resists every attempt to place it under control, and it not unfrequently happens that the strongest iron plates and bars are insufficient to retain it within bounds, and to resist the force and impetuosity of its attack. In fact, it is one of those irresistible agents, when allied to the vapour of water, that gathers strength by confinement, and, like all other great powers, it is either useful or destructive, according to its force; and if we desire to make it useful and turn it to the beneficent purposes of nature, and apply its powers to the wants of man, we must give it room to expand and contract; and this we must do by confining it within such iron bounds as will render it tractable under the varied forms and conditions in which it may be employed. Under those restraints, it will serve you with a fidelity incomparably superior to either of its constituents,—fire and water,—taken singly.

I have expressed myself in this familiar manner in order to bring the subject prominently before you, and to show that in the exercise of an economical distribution of steam as a motive power, we should be most careful to maintain the union of the heat and the water as it passes from the boiler, and during the period of its action on the organization of a machine, like the steam-engine, so well calculated to distribute its force and overcome any resistance to which it may be applied. We look in vain for any other agency to effect this prodigious amount of labour. Such being the case, I am persuaded that in this address I do not ask too much, if I simply require from you the exercise of a judicious and careful supervision. Retain what you have got, preserve your steam, and, in military parlance, "Keep your powder dry." These are the requirements which you are called upon as operative engineers to meet, and I make no doubt you will faithfully and honestly perform your duty.

To produce a maximum mechanical effect with a minimum quantity of steam, two things are essential; first, the prevention of the escape of heat in its transmission from the boiler to the

engine; and, secondly, the working of the steam expansively when you get it there. A great deal has been said of surcharged steam, or steam that is re-heated in its passage from the boiler to the engine. Now, on this important subject I am probably not so well versed as I could wish; but I have endeavoured to discuss it in the previous Lecture, and it yet remains to be seen whether the conclusions I have arrived at be such as are borne out by the facts. In order, however, to retain the heat and prevent any diminution of temperature in the steam, I have on several occasions suspended the steam-pipes in the heated flues as they pass from the boiler to the engine, and this plan I can say is not only economical, but it prevents condensation, and conveys to the engine what is technically called anhydrous or dry steam. It is further desirable to make use of the surplus heat for increasing the temperature of the water from the feed-pump, by enclosing those pipes also in the flues, or by exposing a series of pipes to the action of the heated currents as they pass from the boiler to the chimney, a method already applied, and that successfully, by an apparatus constructed by Mr. Smith of Huddersfield.

The expansive action of steam is a question of such vast importance, and so well known, as to require no very lengthened description in this place; suffice it to observe, that the subject has attracted the attention of some of our ablest engineers, and it is now generally acknowledged that a very considerable saving is effected by this system, independently of what is accomplished by the improved methods recommended for the generation and maintenance of the temperature and the density of the steam in the boiler, and in its passage to the engine. To effect this process with increased economy, we must use steam of high pressure; and moreover, we must apply it with a sound discretion, not only as a principle of economy as regards the consumption of steam, but also as a measure of safety as regards the strength of the boiler and the different organic parts of the engine exposed to the action of the steam.

A great variety of ingenious contrivances have been adopted

to effect these objects; of these we may mention Woolf's system of the double cylinder, the "cut off" principle in the single cylinder, and other methods which have been more or less successful.

All these contrivances, however, tend to the same result; and whatever the mechanical arrangement may be, the ultimate tendency is to economize fuel, by the application of a highly elastic force upon the piston of the reciprocating engine in the first instance; and having overcome the *vis inertiæ* of the load, to give the impetus of motion immediately as the piston passes from a state of rest to a state of motion at the return of the stroke. In this way the communication between the boiler and the cylinder is cut off at the required point, and the further motion of the piston is continued by the force of the expanding steam to the end of the stroke.

In this way the constant reciprocating motion of the engine is continued, and that with greatly increased economy in the use of the steam. But on this question I shall enter more at large in the next Lecture.

I could have wished to dilate upon this subject to a much greater extent, but I have already occupied so much of your time as to render any further attempts at illustration perhaps out of place. I have therefore, in conclusion, to ask you to reflect upon the matter I have laid before you; and I trust I am not too sanguine in entertaining a hope that I have impressed you with my own conviction, that the diffusion of sound principles and enlarged views in practical science will not only be useful to ourselves in the pursuit of our separate avocations, but advantageous to every class in the communities of which nations are composed.

LECTURE IX.

ON STEAM AND STEAM BOILERS.

BEFORE entering upon the immediate subject of this and the succeeding Lecture, I trust I may be permitted briefly to allude to the new theory of heat which for the last ten years has received the attention of some of the most distinguished philosophers and men of science of the present day. In my attempts to render the received opinions of the nature and properties of steam as comprehensive as possible, I purposely omitted any notice of this new theory, which for many years has been looked upon as an hypothesis yet to be proved; it has, however, through the experimental researches of my friend Mr. Joule and others, taken its stand as a recognized principle in science; this principle, as now understood, bearing directly upon the varied conditions of water in its solid, fluid, and gaseous state, cannot be otherwise than interesting to the philosopher as well as to the practical engineer. Viewing it in this light, it may not be inappropriate to give you some account of its rise and progress; as well as to direct your attention to the prospects which present themselves for its future development in the progressive advancement of mechanical science.

The theory that heat is not a ponderable substance, has been supported by some of the most distinguished men of science of ancient as well as of modern times; but it was reserved for Mr. Joule to prove by experiment, the definite evolution of heat by the expenditure of mechanical force; and he not only determined the conversion of heat and mechanical effect, but he

ascertained the proportion which they bear to each other in cases of mutual conversion.

In his paper "On the Heat evolved during the Electrolysis of Water" (see Manchester Memoirs, vol. vii. New Series), he observes, that "the magnetic electrical machine enables us to convert mechanical power into heat, by means of the electric currents which are induced by it," a proposition experimentally demonstrated in a paper read before the British Association in the year 1843, in which he also proves, *vice versâ*, that the mechanical power of the electro-magnetic engine is obtained at the expense of the heat due to the chemical reactions taking place. In this and subsequent papers he points out that friction consists in the conversion of mechanical force into heat. Subsequently, in a memoir communicated to the Royal Society, he shows that the heat evolved by the compression of air is the equivalent of the mechanical force used in the compression, and, *vice versâ*, that the heat abstracted by the expansion of air on the removal of pressure is the equivalent of the mechanical force required to produce the requisite displacement of the atmosphere; also that when air is allowed to expand without evolving work, no change of temperature occurs except the very minute one, anticipated and experimentally demonstrated by Professor Thomson, owing to the imperfection of air as an elastic fluid. In concluding this paper, he remarks,—"The principles I have adopted lead to a theory of the steam-engine very different from the one generally received, but at the same time much more accordant with facts. From them we may infer, that the steam, while expanding in the cylinder, loses heat in quantity exactly proportional to the mechanical force which it communicates by means of the piston; and that on the condensation of the steam, the heat thus converted into power is *not* given back. Supposing no loss of heat by radiation, &c., the theory here advanced demands that the heat given out in the condenser shall be less than that communicated to the boiler from the furnace, in exact proportion to the equivalent of mechanical power developed."

These views of Mr. Joule have since been confirmed by successive experiments undertaken by himself, Regnault, Thomson, and others; and the dynamical theory has been developed by the labours of Mayer, Helmholtz, Clausius, Rankine, and especially of Thomson, whose profound investigations entitle him to a principal share of the merit of establishing the new theory.

These authorities are agreed upon the immaterial nature of heat; and nothing can be more interesting than the exactitude and care with which Mr. Joule has pursued his experimental researches on this very interesting and important subject.

In stating the conclusions at which he arrived as to the properties of heat, and its effects on the particles of matter, he says, that the results from those experiments were, that heat and mechanical power were convertible into one another; and it became therefore evident that heat is either the *vis viva* of ponderable particles, or a state of attraction or repulsion capable of generating *vis viva.*

These data were of great importance in showing, "that whenever a current of electricity is generated by a magneto-electrical machine, the quantity of heat evolved by that current has a constant relation to the power required to turn the machine; and on the other hand, that whenever an engine is worked by a voltaic battery, the power developed is at the expense of the calorific power of the battery for a given consumption of zinc; the mechanical effect produced having a fixed relation to the heat lost in the voltaic circle."

Again, it became important to ascertain the exact equivalent of heat, and this was sought for in the heat generated by the friction of fluids. In these experiments, Mr. Joule found,—first, that the expenditure of a certain amount of mechanical power in the agitation of a given fluid, uniformly produced a certain fixed quantity of heat; and secondly, that the quantity of heat evolved in the friction of fluids was entirely uninfluenced by the nature of the liquid employed; for water, oil, and mercury (fluids as diverse from one another as could be well selected) gave

sensibly the same result, viz. that the quantity of heat capable of raising the temperature of a pound of water 1°, is equal to the mechanical power developed by a weight of 770 lbs. (since ascertained to be 772 lbs.) falling through one perpendicular foot."

From these extracts, it will be seen that Mr. Joule has demonstrated, not only the production of heat by the friction of the particles of various substances, but he has determined experimentally the mechanical effect, and fixed the relative proportions which they bear to each other, namely, that so much heat as is sufficient to raise the temperature of one pound of water 1° of Fahrenheit, is sufficient to raise a weight of one pound to a height of 772 feet. This is called Joule's "equivalent," a discovery of vast importance to science, and one that may lead to important results and extensive improvements in the application of heat to steam and other elastic fluids.

I ought to apologize for this long digression, but the bearings of this new theory in connexion with its application to steam and force, must be its own apology, as it leads to considerations of great importance relating to future improvements in the application of steam and other elastic fluids. Mr. Joule's mechanical equivalent of heat gives us the maximum work which a unit of caloric will perform: now our very best steam-engines do not perform more than one-fifth of this work; hence we are led to conclude that these engines still admit of considerable improvement. Already much is being done in this way by the use of steam of high temperature, as well as by the employment of super-heated steam; and it would argue a very contracted view of mechanical progress to assert, that we have already attained a maximum result, when, in fact, there is probably no maximum as regards human progress. We are always learning; and the constant developments and discoveries in natural science are sufficient proofs of the advantages that have yet to be attained in the pursuit of knowledge, and more particularly that kind of knowledge which has for its object the opening of the page of nature for the instruction of the human

intellect. These remarks, which have reference to future improvements and progress in practical science, have not been altogether lost sight of; as the air-engines of Stirling and Ericson, and the combined steam- and ether-engine of Trembley, abundantly testify in attempts made by practical men to avail themselves of the law of the convertibility of heat into mechanical force. The first two failed, not from the principle of using air successively heated, expanded, and cooled and compressed; but from practical difficulties in the retention of the heated currents, and the high temperature to which the material of the receivers and the working parts of the engine were subjected. The same observations will apply to almost every description of air-engine; but that of Trembley is widely different, as he works his steam at a comparatively low temperature, and ether, which evaporates at a still lower temperature, can produce no injurious effects upon the organic parts of the engine or cylinders.

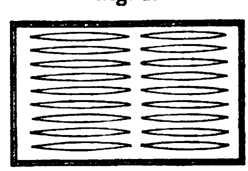
The most successful application that has yet been made of the new theory of the conversion of heat into mechanical effect, is probably the engine of Siemen. This engine, which is designated the Regenerative Engine, deserves more than a passing notice. It is constructed on nearly the same principle as Stirling and Ericson's air-engine; but instead of using heated air according to the laws of Mariotte and Gay-Lussac, he uses saturated steam upon the same principle, or in other words, upon the principle of the respirator or regenerator; wherein, by the peculiar construction of the cylinders and vessels of the engine, the steam travels (if I may use the expression) in a circle, taking up and giving out heat as it flows out of one cylinder into another.

In Mr. Siemen's engine there are three cylinders, two of them with plungers, and one with a piston of the usual construction. Under each of the plunger cylinders, is a fire which raises the steam as it enters from the steam-cylinder to a temperature of 550° to 600° of Fahrenheit. Part of this heat is lost in mechanical effect, or work done, as it acts upon the

plungers by expansion; and the remainder of the heat, or the greater portion of it, is extracted or taken up by the respirator or regenerator as it passes to the steam-cylinder, where the additional mechanical force is effected at a reduced temperature in the ordinary way upon the piston of the steam-cylinder. In this way the steam is worked *over and over again,* constantly receiving and parting with its heat; and thus, by a continued series of convertibilities of ascending and descending temperatures, the work in foot-pounds, as it is called, is produced. It will not be necessary, in this brief notice, to go further into the details of the engine or its construction; suffice it to observe, that it performs a very satisfactory duty, and although far from perfect, the results of repeated trials and tests show that there is a saving (as stated by Mr. Siemen) of at least one-half of the fuel used by the ordinary steam-engine in performing the same quantity of work.

Amongst other improvements of the present day, there still remains the steam- and ether-engine of Mr. Trembley, which, from its novelty and superior economy of fuel, is well entitled to consideration. This engine consists of a steam-engine of the ordinary construction, with a tubular condenser of the annexed sectional form. These tubes are fixed in a steam-tight case, and instead of water surrounding the tubes for the purpose of condensation, ether or chloroform is substituted. Now, as either of these fluids boils at a temperature far below that of water, the effect is, that the tubes, in place of being used as a condenser, become, by the heated currents of the exhaust steam which flows from the engine, the generator of the vapour of ether up as high as 10 lbs. on the square inch. The steam in this case parts with its heat to the ether, and by these means is condensed nearly to the temperature of the vapour of ether so formed. The vapour or steam of ether or chloroform, thus produced, gives motion to the piston of a second and connected cylinder, and these two forces combined comprise the power and economy of the steam-

Fig. 1.



and ether-engine. Ether, as well as chloroform, being expensive, it becomes absolutely necessary to use it in perfectly tight vessels; and the greatest economy must be observed in order to prevent injurious effects as regards the health of the attendants, as well as the saving of the material.

Several of those engines are now at work in the French Navy, as I am informed with good results, by which a considerable saving of fuel is effected. The only danger apprehended, is the loss sustained in the condensation of the vapour, and the risk of pumping it over and over again in a continuous stream from the condenser to the generator.

After all, it becomes a question well entitled to consideration, whether the simple element of steam from water is, or is not, the best for obtaining the most satisfactory dynamic effect. All these forces, and the economy of their application are within the steam itself; and we have only, in my opinion, to render the heat which is latent in any given volume *sensible,* to effect a greatly increased economy; and at the same time, by rendering the expansive action of steam sufficiently extended, we may then look forward to a close approximation of what may be considered *theoretically* a perfect engine.

Having glanced at the important discoveries which of late years have burst upon us from the experiments of Joule, Thomson, Regnault, and also from the various schemes and projects which have been brought forward in connexion with theories formerly unsupported by physical truth, but now clearly established by experimental facts and researches which I have brought before you in as concise a form as the importance of the subject would admit,—and as all these are more or less connected with steam or some other elastic fluid of great force,—our next consideration will be to inquire into *the strength and form of vessels calculated to retain, with safety, steam of high elastic force*; and in the pursuit of this inquiry we shall have to treat,—

1. Of the material used in the construction of boilers; and

2. Of the distribution of the material and form best calculated to ensure the maximum of strength.

Our attempts at new discoveries and improvements of steam at increased density and pressure would be of no avail, unless the generators and receivers were made of proportionate strength and security. To these points, in the remainder of this and the succeeding Lecture, I shall therefore direct your careful attention. In the two lectures which I gave to the Yorkshire Mechanics' Institution in 1851, I went carefully into the subject of the strength of the material used, the best forms, and the soundest principle upon which the material composing a boiler should be united in order to attain a maximum power of resistance. I did not, however, show in sufficient detail how this could be accomplished, nor did I point out other measures of economy and safety which in the discussion of this subject appear to be absolutely necessary in order to arrive at sound practical results. These omissions I now propose to supply; and before entering upon the consideration of the question, we shall briefly review the various improvements and conditions of boiler constructions from the earliest period of the steam-engine up to the present time.

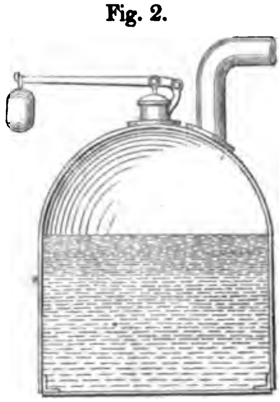
In speaking of vessels calculated to raise steam, as a matter of course I mean boilers whatever may be their form, or the object for which they are intended; and we shall therefore, in the considerations we have to offer, view them as such, and that in accordance with the above division or classification.

1. *Of the material used in construction.*

Until the days of Savery, Newcomen, and Watt, it may with perfect safety be asserted that the vessels used for boiling—we cannot call it steaming—were composed of a great variety of material, such as copper, earthenware, and other substances calculated to resist the action of fire, and to fuse at a temperature considerably above that of boiling water. At an earlier period of our history, when the Marquis of Worcester first attempted the use of steam as a motive power, the philosophers and scientific men of that day had very imperfect ideas of steam or its properties, as now understood. Dr. Papin, it is true,

discovered a method of dissolving bones and other animal solids in water by confining them in close vessels, which he called "Digesters;" but it was reserved for Dr. Hooke, in 1686, to discover that water could not be made to acquire above a certain temperature in the open air, and that as soon as it begins to boil, its temperature remains fixed, and an increase of heat only produces a more violent ebullition and a more rapid evaporation. Papin's experiments at a later date, however, made the elastic force of steam in confined vessels more familiar; and Captain Savery, availing himself of this discovery, very adroitly applied that power, combined with condensation, to an engine for raising water, which he revealed to the world in a book published in 1696, entitled "The Miner's Friend."

Fig. 2.

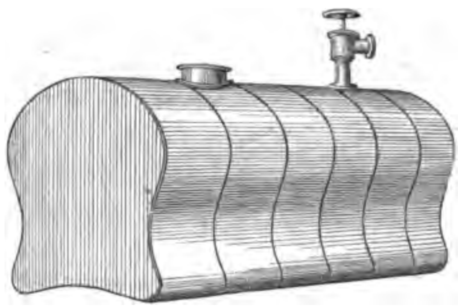


Captain Savery's steam-boiler, fig. 2, probably the first that was made, was composed of copper, of the annexed form, and riveted together with rivets of the same material. Copper, although a better conductor of heat than iron, was, however, found to be an expensive material for the construction of boilers; and it is not improbable, that before Newcomen's improvements came into use, iron plates were employed in boiler construction. Cast iron was also used about this time, but it was not until the great superiority in the strength of malleable iron plates became more generally known, that the cast-iron constructions were discontinued.

Cast iron has now become obsolete, but copper maintains its place, particularly in situations such as the fire-boxes of locomotive boilers, where its application is preferable to that of iron. Mr. Watt almost from the first made use of wrought iron in the construction of his boilers: I believe they were at first made like those of Savery, Newcomen, and Beighton, of the haycock shape, but the fertile genius of Watt soon discovered that the

longitudinal or waggon-shape, as shown in fig. 3, was preferable to those designed and used by Newcomen and Beighton.

Fig. 3.



It is probable that Watt did not, in the midst of his many discoveries, pay so much attention to the strength as to the form of the boiler. In fact he had taken every precaution to prevent accident by his self-feeding and self-acting apparatus in relieving the pressure by the initial force of the steam, to overcome the resistance of a column of water, whenever its force exceeded the pressure at which the boiler was calculated to work; and this seldom or never exceeded 7 or 8 lbs. per square inch above that of the atmosphere. Hornblower, Woolf, and others, who employed steam at a higher pressure, had to alter the shape of their boilers, and adopt the cylindrical form, with or without internal flues; similar in fact to those so long used in Cornwall and other districts, where steam of greater density and pressure was employed.

In this inquiry it may, however, be necessary to lay before you the relative strength of the different material of which boilers are composed, and subsequently to show how it may best be applied with economy and effect.

This is a consideration of considerable importance to every engineer; and in order to arrive at a just conception as respects the quality of the material, it may be desirable, first, to ascertain the nature of the strains to which, in these constructions, the material is exposed; and secondly, to determine how it should

be placed or distributed in order to arrive at the maximum power of resistance.

Now, in boilers having internal flues or tubes, there are two kinds of strain to which they are subjected; namely, one having a tendency to tear or rip up the outer shell by tension, and the other to crush or collapse the internal flues or tubes by compression. These two forces are continually in operation when the boiler is at work, and what we have to do in these considerations, is to calculate not only the kind of material to be employed in its power of resistance to those strains, but we should endeavour to place it in such form and position as would enable it to do so with a maximum effect. Wrought iron and copper plates are much better calculated to resist a tensile strain than cast iron, as may be seen from the following numbers, which represent the relative strengths or powers of resistance of each, per square inch, to tension and compression:—

The resisting powers of	Tension in tons.	Compression in tons.
Wrought iron plates to	23	12
Copper „	16	3
Cast iron „	8	51

From this, will at once be perceived the great difference which exists between the resistance of the different metals, to a tensile and a compressive strain. In wrought iron it is as 23 to 12; in copper as 16 to 3; and in cast iron as 8 to 51. Now in these varied conditions of resistance of the different metals, it is of incalculable benefit that we should know which of them is the most eligible, and which to employ in our varied constructions, and that more particularly when the nature of the strain is considered.

To employ the right description of material is as essential as to employ knowledge and skill in sound construction. If, for example, we were to place cast iron in a position where its powers are to be tested by tension, and wrought iron or copper where its powers are to be subjected to compression, it would be a gross error of judgment; for we know that wrought iron will sustain three or four times more force in its resistance to

direct cohesion than cast iron; and on the other hand, it would be equally erroneous if we were to employ wrought iron or copper to resist compression, when we know that cast iron will resist that force from 4 to 16 times better than either of them.

Now all this knowledge is truly useful, as it applies with considerable force to the rules of direct practice, and that more particularly in the construction of vessels operated upon by two distinct forces, which, if left uncontrolled, would prove sufficiently powerful to break through all bounds of restraint.

In submitting these facts to your consideration, I have not entered upon the question of elongation by tension or of contraction of bulk by compression. These are facts not only curious and interesting in themselves, but more or less peculiar to the behaviour of different kinds of materials under strain. We must, however, leave them for the present, and with these observations proceed to show in what form, and in what way, this material—iron (as now generally used)—should be distributed in order to attain the greatest possible strength with the minimum quantity of material.

2. *On the distribution of the material and form best calculated to ensure the maximum of strength.*

These are considerations in every kind of structure which should never be lost sight of; they are the very essence of constructive science; and he is only a blunderer who neither possesses the skill nor the knowledge to turn them to account.

It is true, that in the employment of a single homogeneous material these desiderata cannot always be obtained; but it is nevertheless our duty to consult the exact sciences as to how we should exercise those powers in order to meet the opposing forces equably and with uniform powers of resistance on all sides. It is this discrimination which constitutes the difference between a man versed in practical science, and one who follows no rule but his own imperfect conceptions, which

lead to error; or gives up his judgment to others, and descends to the position of a mere copyist.

I have already shown what was the state of our knowledge, and what were the forms of vessels containing steam, in the early stages of the history of the steam-engine; and I now come to explain to you the various forms and conditions in which these vessels have been constructed from that period up to the present time; and in order to accomplish this object in a satisfactory manner, I shall treat the matter somewhat historically in the first instance, and then I shall urge upon your attention the necessity of adhering to those experimental facts, or rather to those unerring laws, which nature prescribes for our guidance and which never fail to lead to sound results.

The discoveries of Watt,—who made the steam-engine what it now is,—who effected condensation in a separate vessel, and who added to the force of the steam a pressure nearly equal to that of the atmosphere,—are on record for our guidance. These discoveries rendered steam of high density at that time unnecessary, when the forces required could be obtained without risk or danger of rupture to the generator or boiler containing the steam; and although this system of working at comparatively low pressure continued for many years, it was nevertheless accompanied with considerable cost, when compared with the cost of working steam of greater density and pressure such as is now in use. Indeed, the wants and necessities of the public were not so great at that time; but as the operations of mines and manufactories advanced, they gradually created new demands; and as increased power was required, it was found that the increase of pressure was the most direct and the easiest way of obtaining it. It was also found, that in pumping from deep mines where large masses of matter such as pumps and pump rods had to reciprocate and to be moved from a state of rest to a state of motion, high steam, worked expansively, was the cheapest and most effective mode of overcoming the "vis inertiæ" of the mass, and of giving the first impulse to the resistance of the load. It was this consideration which first

induced the Cornish miners to work with high steam, and hence followed the necessity of employing boilers of improved form and of greater strength. It must be borne in mind, that, before the use of high steam, the calculation of strength was not a subject of so much importance as form, and this did not escape the far-seeing and consummate skill of Watt. His boiler (the waggon-shape) had reference to a large heating surface, and those parts, such as the sides and ends, that were liable to bulge outwards, were held together by iron stay-rods transversely and longitudinally attached to the sides and ends. This form is, however, very objectionable for high-pressure steam; and although it kept its ground for more than half a century, it had nevertheless at last to give way to a stronger form and a much better system of construction.

The low-pressure condensing-engine of Watt was universally in use from the beginning of this century up to nearly the present time. On the continent and in Cornwall, where fuel was expensive, the question of economy and effect was freely and energetically discussed, and at an early period of the history of the steam-engine the system of high steam, worked expansively, was not lost sight of. Woolf's plan of the double cylinder, and Mr. Watt and Mr. Murdoch's system of obtaining the same results by cutting off the steam in the single cylinder, was in mining operations found highly advantageous. Both methods were adopted in the mining districts; but in the seat of the manufactories there was less inducement to change, and it is only within a period of ten or twelve years, owing to the increase of manufactures and the corresponding increase in the price of coal, that the saving consequent upon the use of high steam was appreciated. In America and the continent of Europe, things were different; and in order to save the expense of fuel at a high rate of cost, the system of Woolf with high and low pressure cylinders was adopted, and that with a saving in some cases amounting to upwards of 30 per cent. These savings were of great value, and notwithstanding the increased risk of failure in the boilers, this circumstance did not deter the pro-

prietors of steam-engines from availing themselves of the advantages which this improved system of working high steam evidently presented.

I remember, many years ago, when urging upon the public the advantages of working high steam expansively, that I was met by an outcry of danger, bursting boilers, &c.; and many went so far as to maintain that there was no saving in the high-pressure system. To meet these assertions, I published, at different times, the views I entertained upon the subject; and in these publications, I endeavoured to prove by actual calculation that there was not only a very considerable saving in the consumption of fuel effected, but a great increase of power was obtained.

It is true, that objections were taken against the single engine working expansively on the score of irregularity of motion; and it is equally true, that the double-cylinder engine is preferable in that respect; but it is a mistake to suppose that any saving of fuel is accomplished by the double-cylinder engine over that of the single one, when the two are worked at the same rate of expansion and the same pressure of steam. All the difference is, that a want of uniformity is observable in the single engine, owing to the sudden reduction of the pressure when the steam is cut off; whereas that of the double cylinder expands more gradually, and thus effects a greater degree of uniformity of action upon the piston. These irregularities in the single engine are however of much less importance than most persons imagine, as the evil is easily remedied by increasing the weight of the fly-wheel, or what is the same thing, by increasing the velocity of the engine till such time as the fly-wheel acquires the ascendant over the changes of pressure upon the piston, or when the irregularities of the stroke become neutralized by velocity in place of weight. When two engines are worked together at right angles, these discrepancies disappear, and the engines under such circumstances may be worked with perfect safety through the whole range of expansive action. It is for these reasons, and a strong desire to

introduce simplicity into every mechanical construction, that I advocate the single engine. It is less expensive, equally efficacious, and in every respect equally, if not more economical, than that of a machine of greater complexity of construction.

With all these facts before us, and taking into consideration the superior economy of high steam, *worked expansively*, it is quite evident, that in all future constructions, either of boilers or engines, we must look forward to the use of a greatly increased, instead of a reduced pressure of steam. Indeed, I am so thoroughly convinced of the advantages inseparable from this application, as to urge upon you the necessity of preparing for greatly increased progress, and greatly increased pressure in all the requirements, appliance and economics of steam as a motive power. It must appear obvious to every reflecting mind, that steam generated under pressure, and compressed into one-fifth or one-sixth the space that it formerly occupied, and that again applied to an engine of little more than one-third the bulk, must be a desideratum in the appliance of an agent so powerful, and so extensively used. Look at our locomotives of the present day, and tell me whether we are, or are not successfully progressing in effecting a closer alliance between the two sister sciences of mechanics and physics; and tell me whether or not the community is not secured equally well from risk, and greatly benefited by the change? Let us calculate, for example, the duty performed, and the force applied to one of our largest class of locomotive engines travelling with a train at the rate of 45 miles an hour, and we shall find the amount of power given out to exceed that of 700 horses, or as much as would be required to drive the machinery in some of our largest factories. And why not work our factories upon this principle? and why not propel our largest ships by engines of this description? There is no reason why it should not be done, and that with greatly increased economy, by introducing a well-directed system of condensation along with that of highly attenuated steam.

I give you these impressions from a conviction of their utility; and I am persuaded the time is not far distant when this will

be accomplished to a much greater extent than may at present be considered possible or safe; and the time is fast approaching, when we shall lessen our space and double our power with greatly increased economy and effect.

How very essential is it, therefore, that we should look forward, and make the requisite preparations for these requirements! and the more effectually to meet them, let us see how we are to unite and distribute our material, so as to ensure safety in retaining for use such a powerful and active agent as that which we have described, and moreover, which we shall assuredly have to deal with, at no very distant period, at greatly increased density and power.

I have already demonstrated, in a former communication, that the cylindrical is the most eligible and the strongest form in which we can place the material, such as iron plates to resist internal pressure; and I have further shown, that we must make considerable reductions in the strength of the material, on account of the riveted joints and the position which the plates may have in relation to the respective junctions of the parts.

The reduction or loss of strength in this alone is about 30 per cent. for the double riveted joints, and 44 per cent. for the single riveted joint; the strengths (calling the plates 100) being in the ratio of 100 : 70 and 56. In our calculations of ultimate strengths, we must therefore make these allowances in order to arrive at correct results*.

As respects form, it has already been proved that the cylindrical and hemispherical (or those forms by which nature is governed in all her constructions relative to pressure) are the best; and it will be necessary only to observe what has already been forcibly urged upon your attention, namely to avoid, under certain conditions, flat surfaces, and to adopt the spherical or

* In a previous investigation, I found that 34,000 lbs. to the square inch was the ultimate strength of boilers having their joints crossed and soundly riveted. On further inquiry, I see no reason to change this opinion, as it has been fully confirmed by subsequent experience.

cylindrical forms wherever and under whatever conditions they are admissible.

This cannot, however, at all times be accomplished; and that flat surfaces should be made to resist severe pressure, is not unfrequently an essential point in construction. Now these flat surfaces are not so very objectionable on the score of strength as they appear to be at first sight. On the contrary, they are, when properly stayed, the strongest part of the construction; and this I have proved by direct experiment, the results of which I will take the liberty to quote for your information, as given in a paper read before the British Association for the Advancement of Science. With respect to the locomotive boiler, it is observed that "the statements contained in the earlier part of this paper regarding the strength of the stays of the fire-box would have been incomplete if we had not put those parts of a locomotive boiler, comprised in the flat surfaces or sides of a fire-box, to the test of experiment. This was done with more than usual care; and in order to attain conclusive results, two thin boxes, each 22 inches square and 3 inches deep, were constructed; the one corresponding in every respect to the sides of the fire-box, distance of the stays, &c., the same as those which composed the exploded boiler; and the other formed of the same thickness of plates, but different in the mode of staying, which in place of being in squares of 5 inches asunder, as those contained in the boiler which burst, were inserted in squares of 4 inches asunder. In fact, they were formed after the manner shown in the annexed sketches (figs. 4 and 5),—the first containing 16 squares of 25 inches area, representing the exploded boiler, or old construction; and the other, with 25 squares of 16 inches area, representing the new construction.

Fig. 4.

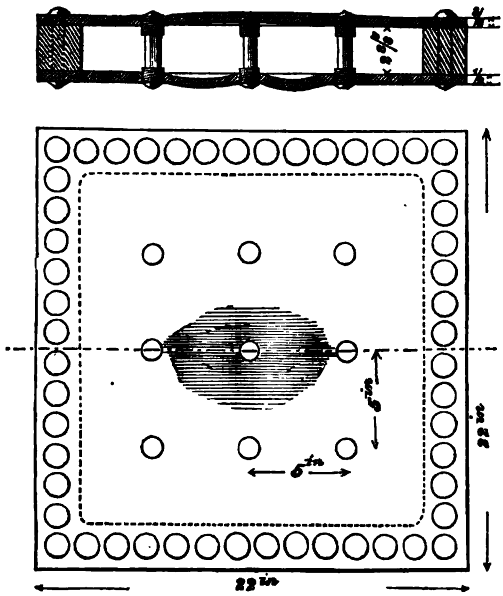
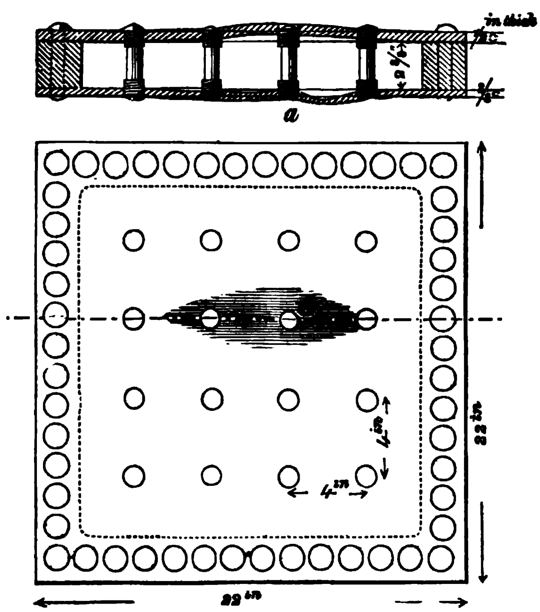


Fig. 5.



"To the flat boxes thus constructed, the same lever, valve, and weight were attached as used in the previous experiments; and having applied the pumps of an hydraulic press, the following results were obtained:—

"TABLE III.

"*Experiment* 1*st*.—To determine the ultimate Strength of the Flat Surfaces of Locomotive Boilers when divided into squares of 25 inches area*.

Number of experiments.	Pressure in pounds per square inch.	Swelling of the sides in inches.	Number of experiments.	Pressure in pounds per square inch.	Swelling of the sides in inches.
1.	245	+	11.	545	·05
2.	275	+	12.	575	·05
3.	305	+	13.	605	·06
4.	335	+	14.	635	·06
5.	365	+	15.	665	·06
6.	395	+	16.	695	·07
7.	425	+	17.	725	·07
8.	455	·03	18.	755	·07
9.	485	·03	19.	785	·08
10.	515	·04	20.	815	

"REMARKS.—*Experiment No*. 4. The box representing a portion of the flat surface of the side of the fire-box of a locomotive boiler was composed of a copper plate, on one side half an inch thick, and an iron plate on the other three-eighths of an inch thick, being the same in every respect as the boiler which exploded, and according to the dimensions exhibited in the drawings, fig. 4.

"*Experiment No*. 20. Burst by drawing the head of one of the stays through the copper, which from its ductility offered less resistance to pressure in that part where the stay was inserted.

"The above experiments are at once conclusive as to the superior strength of the flat surfaces of a locomotive fire-box, as compared with the top or even the cylindrical part of the boiler; but taking the next experiment, where the stays are closer together, or where the areas of the spaces are only 16 instead of 25 square inches, we have an enormous resisting power; a force much greater than anything that can possibly be attained, however good the construction, in any other part of the boiler.

* These and the following Tables are taken from Appendix, No. II. in order to enable the reader to consult them with greater facility.

"TABLE IV.

"*Experiment 2nd.*—To determine the ultimate Strength of the Flat Surfaces of Locomotive Boilers when divided into squares of 16 inches area.

Number of experiments.	Pressure in pounds per square inch.	Swelling of the sides in inches.	Number of experiments.	Pressure in pounds per square inch.	Swelling of the sides in inches.
1.	245		25.	965	·09
2.	275		26.	995	...
3.	305		27.	1025	·
4.	335		28.	1055	
5.	365		29.	1085	
6.	395		30.	1115	
7.	425		31.	1145	
8.	455		32.	1175	
9.	485		33.	1205	
10.	515	·04	34.	1235	
11.	545	·04	35.	1265	
12.	575	·04	36.	1295	·09
13.	605	·06	37.	1325	·09
14.	635	·06	38.	1355	·10
15.	665	·07	39.	1385	·11
16.	695	·07	40.	1415	·11
17.	725	·07	41.	1445	·12
18.	755	·08	42.	1475	·13
19.	785	·08	43.	1595	·14
20.	815	·08	44.	1535	·16
21.	845	·08	45.	1565	·22
22.	875	·08	46.	1595	·34
23.	905	·08	47.	1625	
24.	935	·08			

"REMARKS.—*Experiment No.* 4. The flat box on which these experiments were made has the same thickness of plates as that experimented upon in the preceding Table, viz. one side of copper half an inch thick, and the other of iron three-eighths thick. The only difference between the two is the distance of the stays, the first being in squares of 25 inches area, and the other in squares of 16 inches area.

"*Experiment No.* 26. From 995 to 1295 lbs., the swelling or bulge on the side was inappreciable.

"*Experiment No.* 47. Failed by one of the stays drawing through the iron plate after sustaining the pressure upwards of 1½ minute.

"In the above experiments, it will be observed that the weakest part of the box was not in the copper, but in the iron plates, which gave way by stripping or tearing asunder the threads or screws in part of the iron plate at the end of the stay marked *a*, fig. 5.

"The mathematical theory would lead us to expect that the strength of the plates would be inversely as the surfaces between the stays; but a comparison of the results of these experiments

shows that the strength decreases in a higher ratio than the increase of space between the stays. Thus, according to the mathematical theory, we should have—

$$\text{Ult. strength 2nd plate per sq. in.} = \text{strength 1st plate} \times \tfrac{25}{16}$$
$$= 815 \times \tfrac{25}{16} = 1273 \text{ lbs.}$$

Now this plate sustained 1625 lbs. per square inch, showing an excess of about one-fourth above that indicated by the law.

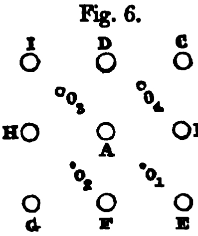
"This is an excess of the force required to strip the screw of a stay $\frac{11}{16}$ths of an inch in diameter, such as those which formed the support of the flat surfaces in the exploded boiler.

"It will be found that a close analogy exists throughout the whole experiments, as respects the strengths of the stays when screwed into the plates, whether of copper or iron; and that the riveting of the ends of the stays adds to their retaining powers an increased strength of nearly 14 per cent. to that which the simple screw affords. The difference between a fire-box stay when simply screwed into the plate and when riveted at the ends is therefore in the ratio of 100 : 76, nearly the same as shown by experiment in the Appendix.

"It is desirable that we should determine, by mathematical investigation, the strain exerted on each stay or bolt of the fire-box.

"Let A, B, C, D, E, F represent the ends of the bolts or stays; O_1, O_2, O_3, O_4 the centres of the squares formed by the bolts. Suppose a pressure to be applied at each of the points O_1; O_2, O_3, O_4 equal to the whole pressure on each of the squares, then the central bolt A will sustain one-fourth of the pressure applied at O_1, also one-fourth of the pressure applied at O_2, and so on; so that the whole pressure on A will be equal to the pressure applied to one of the square surfaces. Hence we have—

Fig. 6.



$$\text{Strain on the stay of Table III.} = \frac{815 \times 25}{2240} = 9 \text{ tons.}$$

$$\text{Strain on the stay of Table IV.} = \frac{1625 \times 16}{2240} = 11\tfrac{1}{2} \text{ tons.}$$

"The stay in the latter case was $\frac{13}{16}$ths of an inch in diameter; hence the strain upon one square section would be about 13 tons, which is considerably within the limits of rupture of wrought iron under a tensile force*.

"In the experiments here referred to, it must be borne in mind that they were made on plates and stays at a temperature not exceeding 50° of Fahrenheit; and the question naturally occurs, as to what would be the difference of strength under the influence of a greatly increased temperature in the water surrounding the fire-box, and that of the incandescent fuel acting upon the opposite surface of the plates.

"This is a question not easily answered, as we have no experimental facts sufficiently accurate to refer to; and the difference of temperature of the furnace on one side, as compared with that of the water on the other, increases the difficulty, and renders any investigation exceedingly unsatisfactory. Judging, however, from practical experience and observation, I am inclined to think that the strengths of the metals are not much deteriorated. My experiments on the effects of temperature on cast-iron† do not indicate much loss of strength up to a temperature of 600°. Assuming therefore that copper and wrought-iron plates follow the same law, and taking into account the rapid conducting powers of the former, we may reasonably conclude that the resisting powers of the plates and stays of locomotive boilers are not seriously affected by the increased temperature to which they are subjected in a regular course of working. This part of the subject is, however, entitled to further consideration; and I trust that some of our able and intelligent superintendents will institute further inquiries into a question which involves considerations of some importance to the public, as well as to the advancement of our knowledge in practical science."

After these results, and the investigations given on a previous

* For the remainder of the experiments, see Appendix, No. II.

† *Vide* Transactions of the British Association for the Advancement of Science, vol. vi. p. 486.

occasion on the form and strength of Boilers*, it will not be necessary to pursue this part of the subject further than to observe, that in every construction of vessel calculated to generate steam of high elastic force, we should preserve a large margin of strength as regards the working pressure and the ultimate power of resistance. Six times the working pressure is not too much to provide for contingences, and vessels so constructed are better calculated to avert danger from explosion than those whose powers of resistance verge upon that of the bursting pressure.

* *Vide* Lectures on Boiler Construction, given to the Yorkshire Union of Mechanics' Institutes at Leeds in May 1851.

LECTURE X.

ON STEAM AND STEAM BOILERS.

WHEN last I had the honour of addressing you, it was upon the strength and form of vessels calculated to hold steam of high elastic force, and in these inquiries I endeavoured to show the necessity of attending to two things:—

1st. The material, and

2nd. Its distribution, and the form in which it should be applied to effect the greatest power of resistance.

In the consideration of these objects I had reference to vessels subjected to internal pressure, having a tendency to force the vessel open, or to tear the parts asunder. This force or tendency to rupture from a tensile strain is probably the most common to which boilers are subjected; but we have other forces to guard against, such as that which arises from collapse, which, I regret to say, has not in some constructions received that attention which the importance of the subject demands.

It is well known to every person at all conversant with the construction of the steam-engine, that a very considerable proportion of our boilers have internal flues, some of them of large diameter; and these, being surrounded by water, are compressed in every direction with the same force as the steam which acts upon their surface.

Now, it is evident that an internal flue, such as we have described, unless it is made perfectly cylindrical, is liable to lose its shape, and to become a flattened instead of an arched or cylindrical surface. Whenever this takes place, its power of resistance is very seriously reduced; and unless the utmost

care and attention be observed, collapse with all its attendant calamities are sure to be the result.

The thickness of plates, the diameter of the tubes, and the position as well as the form of the flues are all points of consideration; but unfortunately we have no precise data on which to establish formulæ for calculating the strengths of those parts; and in the present state of our knowledge we are left to guess at the strengths and the capabilities of sustaining resistance in those positions to which we have referred. It is more than probable that the strengths will be for the same thickness of plates as the diameters; but we are entirely at a loss to determine what diameter of flue and what thickness of plates may be necessary to give uniformity of strength in every part of a boiler so constructed. In the absence of these data, I must reserve the investigation of the question till I have an opportunity of establishing by actual experiment the laws of resistance to collapse under different forms of construction. As soon as those facts have been ascertained, we shall then be able to effect constructions on principles calculated to ensure uniformity of strength under the combined forces of tension and compression. In the meantime, I shall avail myself of a Table of strengths showing the safe working-pressure and ultimate powers of resistance in boilers of different dimensions.

This Table is computed from my own experiments on the strength of iron plates, and is introduced to the public with the following observations by Mr. Cowburn:—

"It has been found by actual experiment that good English forged iron will bear a strain of 25 tons to the square inch, that is, a bar 1 inch square, or a plate of wrought iron containing 1 inch of sectional area, will require 25 tons, or 56,000 lbs., to wrench it asunder; but Mr. Fairbairn states, that 'plates when riveted together are reduced in strength from the fact that nearly one-third of the material is punched out for the reception of the rivets,' and therefore he takes 34,000 lbs. as equal to the strength of riveted plates containing 1 inch of sectional area. The following Tables are

deduced from the assumption that 34,000 lbs. per square inch is the tensile resistance of wrought iron plates. The Tables show at a glance what different diameters and thicknesses of plates are required for a safe working pressure, viz. one-sixth of their actual strength, when made of good material and workmanship. It should be observed, that the ends, if properly made and stayed, have only half the pressure exerted upon them that the diameter has, so that they have only to resist one-twelfth of their strength."

Diameters of boilers.		Working-pressure for ⅜th-inch plates.	Bursting-pressure for ⅜th-inch plates.	Working-pressure for ½-inch plates.	Bursting-pressure for ½-inch plates.
Feet	inches.	Pounds.	Pounds.	Pounds.	Pounds.
3	0	118	708¼	157¼	944¼
3	3	109	653¾	145¼	871¾
3	6	101	607	134¾	809½
3	9	94½	566½	125¾	755½
4	0	88½	531	118	708½
4	3	83¼	500	111	666½
4	6	78¾	472	104¾	629½
4	9	74½	447¼	99¼	596¼
5	0	70¾	425	94½	566½
5	3	67¼	404¾	89¾	539½
5	6	64¾	386¼	85¾	515
5	9	61½	369½	82	492¾
6	0	59	354	78¾	472
6	3	56½	340	75½	453¼
6	6	54¼	326¾	72½	435¾
6	9	52¼	314¾	69¾	419½
7	0	50½	303½	67¼	404½
7	3	48¾	293	65	396¾
7	6	47	283¼	62¾	377½
7	9	45½	274	60¾	365½
8	0	44	265¾	59	354
8	3	42¾	257½	57	343¼
8	6	41½	250	55½	333¼

Rule for ⅜th-inch Plates.—Divide 4·250 by the diameter of the boiler in inches, the quotient is the working-pressure, being one-sixth the strength of the joints.

Rule for ½-inch Plates.—Divide 5666·6 by the diameter of the boiler in inches, and the quotient will be the greatest pressure that the boiler should work at when new, that is, at one-sixth the actual strength of the punched iron.

Having supplied every known fact in connexion with construction, we now proceed to the consideration of other circumstances closely allied to those of security and economy. In pursuing these inquiries, it will, however, be necessary for us to follow the same consecutive system that we have adopted on

former occasions, that is, by dividing the subject into sections as follows:—

1. On the proportion, or relative value of the surfaces of the furnace to the absorbent surfaces as the recipients of heat.

2. On the safety-valves and other adjuncts calculated to ensure safety.

3. On high-pressure steam worked expansively.

4. On management.

1. *On the proportion, or relative value of the surfaces of the furnace to the absorbent surfaces as the recipients of heat.*

I have to observe that, on this question, there is great diversity of opinion, as much depends upon the quality of the fuel used, and the rate at which it is consumed. We have at present no fixed rule for finding the proper proportion of the surface of the grate-bars to that of the boiler exposed to the action of heat. On these points a series of well-conducted experiments are much wanted, in order to determine not only the relative proportions, but also to ascertain the quantities of heat absorbed by the surfaces surrounding the furnace, and at different distances, as these surfaces recede from the immediate source of heat. On this subject we are quite in the dark. Every man on these points is his own doctor, and the wildest theories are consequently promulgated for the good of the public, and as some would have it, for the advancement of science.

It is now some years since I made an attempt to rectify these discrepancies; but I met with so many different forms, and such widely different proportions, as almost induced me to abandon the inquiry as a hopeless task.

I however persevered; and taking the mean of fifteen boilers examined, I found that the ratio of grate-bar surface to that of the boiler surface should be as 1 to 11 nearly. This ratio varied from 1 to 9 up to 1 to 13, the mean being, as before observed, as 1 for the grate-bar surface to 11 for the recipient surface. This investigation took place thirteen or fourteen years ago, before the introduction of the tubular system of boilers.

On comparing the stationary, multi-tubular, marine and locomotive boilers, we find the following ratios of furnace to absorbent surface:—

Stationary boiler . . . . as	1 : 11
Multi-tubular stationary boiler . .	1 : 22
Marine tubular boiler	1 : 20
Locomotive tubular boiler, mean of twelve sorts of engines . . .	1 : 80.

These proportions, although differing from those in use by some engineers, may however be taken as approximately correct, and such as appear to be generally in use for obtaining the best results.

I do not, however, give these proportions as conclusive; on the contrary, I entertain doubts of their accuracy, as the ratios are founded upon no fixed law, but taken from crude observations; they can only be considered as the mean results of general practice, which have yet to be confirmed by actual experiment. On this question we must therefore not be led astray with the impression that the multi-tubular is either the best or the most economical in a commercial point of view. It may, or it may not be so; I contend for it more upon the principle of diffusion and a saving of space, than on any other property it may possess over the flue boiler; and for this simple reason, that we find a multi-tubular stationary boiler, 24 feet long and 7 feet diameter, generate as much steam as a flue boiler of one-fourth greater capacity. It presents nearly double the absorbent surface, but it does not from that cause follow that less fuel is consumed. Several competent judges contend that the expenditure is greater, and amongst them,—no mean authority,—is Mr. C. Wye Williams, who maintains, that so far as regards general efficiency, the flue system is capable of supplying all that is required, while it is free from the anomalies incidental to the multi-tubular plan. He states that "when large quantities of steam are required for larger engines, this can be best obtained, not by additional tiers of tubes, but by extending the areas and length of run, thus increasing the number of units of

time, *distance*, and *surface* along which the heat transmitting influence may be exerted." To prove this, Mr. Williams gives an example in the original boilers built for the Great Western Steamer, having been replaced by others on the multi-tubular principle; and although the relative proportions of the heating surfaces were as 3860 to 7150 square feet, the former was the better and more efficient of the two.

Now, the only way to remove these doubts and differences, and to clear the question of all ambiguity, is to appeal to experiment.

This, I hope, shortly to be able to accomplish, either by the aid of the Royal Society, or by that of the Association now so happily formed at Manchester for the prevention of boiler explosions.

In addition to the relative areas of fire-bar heating surfaces, we must bear in mind, that the proportions just given are those which appear to effect the nearest approach to a maximum duty under conditions widely different from each other as regards the space occupied, and the principle upon which the steam is generated and maintained.

Time is an element which cannot be neglected in the combustion of a certain quantity of fuel, and hence we have three different processes in operation which require attentive consideration, and these three are, *slow*, *active*, and what I shall take the liberty of calling *excited* combustion. Now, the first of these is practised upon a large scale in Cornwall, where the draught is kept down by the damper, and the heated currents make two or three circuits of the boiler at a slow rate; and this affords time for the absorption of the heat during its passage to the chimney.

In the second, there are two kinds, the moderate and the active; the first of these apply to stationary boilers used in manufactories, and the second to those afloat, as used in steamers and ships of war. In stationary boilers, we have every description of treatment, in all its gradations from slow to active combustion, and this arises from one of two causes, or from both.

The first is want of space, and the second want of money or inclination to expend additional sums in the construction of new boilers. When this is the case, active combustion is the only alternative, and that is sometimes carried on with such determined energy as to cause an enormous waste of fuel; equally expensive as respects wear and tear, and productive of that intolerable nuisance so loudly complained of,—*smoke*.

The marine boiler admits of no alternative on the score of combustion: it must be active, as the reduction of space is always a desideratum on board of ship. Much, however, may be done even in these contracted forms to economise fuel by increasing the areas of the recipient surfaces as much as possible; and this is best accomplished by the tubular system, and a wide diffusion of the increments of heat as they pass from the furnace through the tubes, and thence to the water in the boiler.

The last,—excited combustion,—applies almost exclusively to the locomotive engine; and here we shall have to enter upon a brief explanation.

The locomotive boiler is nearly identical in its principle of construction to that of the multi-tubular. It is, however, widely different as respects the process of combustion; as in one case the fire is supplied with oxygen by the rarefied column, or draught of the chimney; whilst in the other the fire is excited with much greater intensity by the blast of steam which passes from the cylinders at great velocity into the chimney. This steam, in its escape to the atmosphere up the funnel, operates upon the smoke-box behind, and through the tubes to the furnace, like a pump, and hence follow the rapid currents of cold air which blow up the furnace, and which never fail to be present when the engine is in motion.

The great beauty of this system therefore is, that "the faster she goes, the harder she blows;" and the fact is, that an engine of this description at a high speed has all the properties of a blow-pipe engaged in exciting and in maintaining an intensity of heat in the furnace almost sufficient to melt the hardest metals. This concentration of the currents upon, and through

the burning fuel, produces a white heat, which would soon destroy the fire-box, but for the great difference which exists between the temperature of the box and the water in the boiler, which seldom or never exceeds 400°; whereas that of the furnace is probably as high as from 1500° to 2000°. From this principle of combustion, it is evident that an intense heat is generated in a comparatively small place in a very short period of time; and hence follows the necessity of having the furnace as well as all the recipient surfaces of heat made of copper, as all the tubes should be made of some similar material having high conducting powers for the transmission of heat.

The absorbent material should also be as thin as possible, in order to save time in the transmission of heat, and to effect a rapid evaporation from the water contained in the boiler. The difference, therefore, between the working of the locomotive and all other descriptions of boilers is, that time, although an element in both processes, is of much greater importance in the one case than in the other, for the locomotive engine boiler will raise as much steam in one hour as a stationary or marine engine boiler will raise in twenty-four hours. To render this a little more explicit, let us examine the subject attentively, and endeavour to account for the difference which exists between two processes which to a casual observer appear to be nearly identical.

It is true, there is little or no difference to be seen between the one process and the other. Stationary boilers have furnaces and flues (tubes, if you like), and so has the other; but mark the difference between the stationary and the locomotive boiler: when the same amount of steam has to be generated, and the same force produced, the latter will generate steam in almost a twentieth part of the time that the other would require to produce the same quantity. This is done with a furnace having only 15 square feet of fire-bar, and is found to be sufficient to supply steam for an engine working at the rate of 700 horse-power, whereas it will require no less than 300 square feet of fire-bar surface to produce the same force in the stationary boiler, the ratio of the surface of fire-bar to that of the boiler being as 1 to 20.

Such is the difference which exists between the two systems; and it appears to me to be a subject of such deep interest, as to require careful investigation in reference to the advantage which we may reasonably hope to attain from a principle only partially developed, and which may in future applications become serviceable to the public. When we have more exactly determined the laws of heat in relation to the generation of steam, the practical application of these laws will, I doubt not, do much for the improvement of the stationary and marine engines as well as for the locomotive engine.

2. *On Safety-Valves and other Adjuncts calculated to ensure Safety.*

This is a subject which for many years has engaged the attention of a great number of persons. It has, like the smoke question, brought forward a vast number of projects; many of them are exceedingly ingenious, but none of them have attained such a degree of perfection, as to render the working of the safety-valve self-acting and free from risk. To go through the whole of the devices and suggestions which have come before the public, would be a task beyond the object of this address, and such as I shall not attempt to inflict upon you at present. Suffice it to observe, that I have collected together some of the best and most useful of them; but as they are already well known, it will be unnecessary to describe them in this place.

Independent of the safety-valves, there are other appendages equally essential to security, and to the generative powers of the boiler,—these are the *Feed apparatus*. Now, in these appliances we have nearly the same variety existing as in the safety-valves: each has its separate advocate; and since the introduction of the high-pressure system, we may safely calculate upon nearly twenty different ways of feeding the boiler.

During the days of Watt the boilers were worked and fed by pumps which supplied a cistern at a height of 10 or 12 feet above the boiler; and the height of this cistern, or the column of water, was the measure of the pressure of steam within the

boiler. On the present system, a column of water could not be used with convenience, as a working-pressure of from 50 to 60 lbs. on the square inch would raise it to a height of 100 feet or upwards, and such a column would not only be inconvenient, but would prove troublesome by its fluctuations, causing an unnecessary surcharge of water in the boiler when the pressure was lowered, and a limited supply when the steam exceeded the fixed degree of working pressure. Under the circumstances, the only alternative left is the employment of a powerful pump, calculated to overcome the resistance of the steam, and to regulate the supply of the water in such quantities by the admission-valve, as will cover the flues and maintain the water at a fixed and uniform height. This is accomplished in a variety of forms: some use a float acting upon the valve, and working through a stuffing-box; and others, simply a screw which regulates the lift of the valve, and increases the supply as the water rises or falls in the boiler. Other useful appendages are attached to high-pressure boilers, such as the glass water gauge, index float, steam and water signals, alarm signals, and other indicators of the state of the water in the boiler. The whole of these are not absolutely necessary, but they can do no harm, if kept clean and in working order.

3. *On High-pressure Steam worked expansively.*

The working of steam expansively is one of the most important subjects to which the engineer can direct his attention. It involves considerations for inquiry into the elementary laws of our present practice, and it leads to a wide field of investigation relative to the varied forms and conditions of any future improvement which we may be called upon to adopt.

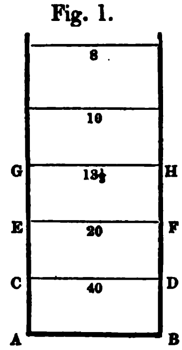
The difference which exists between high and low steam is, according to our present ideas, the measure of its elasticity and temperature when taken at the extremes at which it is worked, viz., from 10 to 150 lbs. on the square inch. When the steam impinges upon the piston at 10 lbs. on the square inch, it generally follows up the supply and pressure continuously

throughout the whole length of the stroke, or nearly so; but when steam of increased density is used, say 50 lbs. upon the square inch, then instead of allowing the steam to act with a constant pressure throughout the whole of the stroke, the communication with the boiler is, at some particular point of the stroke, suddenly intercepted, and the steam, thus cut off, is left to perform the remaining portion of the stroke by its elastic force. In this case, the steam dilates or expands as the piston moves forward, and consequently acts with a constantly decreasing pressure upon the piston, until it arrives at the end of the stroke. This is technically called "working steam expansively."

Let us now examine the subject more minutely, and endeavour to ascertain the relative values of the two systems of high and low steam. It will be found, that in working high-pressure steam expansively, the advantage is greatly in favour of that process, as compared with the non-expansive principle.

If we take a cylinder, such as is shown in the annexed diagram, of any given diameter, say 5 feet long, and divide it into five equal parts, as represented by the lines CD, EF, GH, we shall then have the different equidistant positions of the piston as it ascends from the bottom to the top of the cylinder. Let us now suppose the space ABCD to be filled with steam from the boiler at a pressure of 40 lbs. upon the square inch, and that with this force, the piston is moved from AB to CD, a distance of 1 foot. Now it is obvious, if we cut off or interrupt the flow of steam at this point, that the next foot of the stroke, that is, from CD to EF, will double the space occupied by the steam; and there being no further supply from the boiler, the steam will have to expand itself into double its original volume, and its pressure by this dilatation will be reduced from 40 to 20 lbs. on the square inch. The piston having arrived at EF, with the force thus reduced to 20 lbs. on the square inch, it again moves forward another foot, that is to GH, where the original space

Fig. 1.



occupied by the steam becomes enlarged three times, with a proportionate decrease of pressure in the steam, that is, with a pressure of one-third of 40 lbs., or $13\frac{1}{3}$ lbs. acting upon the piston, and so on to the other points of the stroke. The pressure of the steam at the successive equidistant intervals of the stroke will be as follows: 40 lbs., 20 lbs., $13\frac{1}{3}$ lbs., 10 lbs., and 8 lbs. These pressures, derived from the law of Marriotte, are no doubt slightly in excess, inasmuch as the vapour suffers a loss of temperature upon expansion.

The deductions to be made for this loss of heat and loss of pressure in the process of working can be ascertained by the *indicator*; but for our present purpose, it will be sufficient to assume that there is no loss.

In order to find the work performed by the steam in one stroke of the piston, we shall first find the mean pressures of the steam acting through the successive intervals of the stroke; and then from these mean pressures, we shall find the total mean pressure.

Pressure in the 1st foot of the stroke					$=40$	lbs.
Mean pressure in the		2nd foot	of the	stroke	$=\frac{1}{2}(40+20)=30$	„
„	„	3rd	„	„	$=\frac{1}{2}(20+13\frac{1}{3})=16\frac{2}{3}$	„
„	„	4th	„	„	$=\frac{1}{2}(13\frac{1}{3}+10)=11\frac{2}{3}$	„
„	„	5th	„	„	$=\frac{1}{2}(10+8)=9$	„
					$5 \mid 107\frac{1}{3}$	lbs.
				Total mean pressure...	$21\frac{7}{15}$	lbs.

$\therefore$ The work in one stroke = the mean pressure × the length of the stroke

$$=21\tfrac{7}{15}\times 5=107\tfrac{1}{3}.$$

Now, when the steam acts uniformly throughout the whole of the stroke, the work $=40\times 5=200$. But this work is done with 5 times the quantity of steam that is employed when acting expansively, therefore the work done by an equal quantity of steam is the 5th of 200, or 40. Comparing the numbers $107\frac{1}{3}$ and 40, we find that the steam used expansively performs $2\frac{1}{2}$ times the work that it does when it is used non-expansively, or with a constant pressure.

This simple method of calculating the work performed by the expansion of the steam gives the result a little in excess. The

following method, depending upon Thomas Simpson's rule for finding the area of irregular curved surfaces, is more exact*.

$$\text{Work done expansively} = \tfrac{1}{3}\{40+9+4\,(20+10)+2\times13\tfrac{1}{3}\}=65\tfrac{2}{3}.$$

$$\text{Work done before the steam is cut off} = 40\times1=40.$$

$$\therefore\ \text{The total work in 1 stroke} = 65\tfrac{2}{3}+40=105\tfrac{2}{3},$$

which corresponds very nearly with the work as before found.

In this calculation some allowance must be made for the loss of heat, and consequently the loss of pressure, during the process of expansion, which may be ascertained by diagrams taken from the indicator. This loss of heat by expansion is much greater than is generally imagined, as we seldom find general practice to agree with deductions derived from theoretical calculations.

In this short Lecture, it will not be necessary to give further examples. I have sufficiently demonstrated the advantages peculiar to high pressure steam when worked expansively, and it now only remains for me to direct your attention to the closing part of the subject, which demands the most careful attention, as all our instructions and attempts at economy will prove fruitless unless they are supported by a steady and efficient course of management.

4. *On Management.*

It has ever been the province of the philosopher and man of science to investigate and elaborate, for the good of mankind, all those physical and mathematical truths, which bear upon the wants of civilized society and the development of those laws, which through a succession of ages have been handed down to us. These truths have been still further extended by the inventions and discoveries of the mechanician and those men of practical science whose lives have been devoted to the pursuit, To the researches and labours of those benefactors of the human race, we are indebted for most of the comforts and enjoyments

* *Rule.*—To the sum of the extreme pressures (per square inch) add four times the sum of the even pressures, and two times the sum of the odd pressures; then this sum, multiplied by one-third the distance between the consecutive points at which the pressures are taken, will give the work done expansively on 1 inch of the piston in one stroke.

we now possess; but these are of no avail unless properly used, and carefully managed; and it is to the management of one of these ingenious discoveries,—the safe and economic production of steam,—that I would, in conclusion, direct your attention. To the combined discoveries and inventions of the mechanic and man of science, we are indebted for the steam-engine; and it remains with the possessor to determine to what extent he will make it safe and efficient; for in the *management* of so docile and so powerful an instrument depends its security as well as its effect.

In the faithful discharge of this very important duty, many circumstances concur to render the uses and appliances of steam-power profitable and secure; and I avail myself of this opportunity, to enforce upon your consideration the following suggestions, which, if carried into effect, will doubtless secure to the owners the most important and satisfactory results.

In the steam-engine the boiler is the source of all power, and the quantity of work performed depends upon the quantity of water evaporated, and the quantity of fuel consumed.

Its generative powers, and the way in which those powers are used, are therefore matters of considerable importance; and those who would work with economy, will require to attend to two things—the perfect combustion of the fuel on the one hand, and the transmission as well as the retention of heat on the other. In a well-managed concern, we never hear of safety-valves and feed-pumps being out of order; there is no tampering with such vital organs of safety; everything is in its place, and the self-acting moveable parts of the apparatus, such as valves, stuffing-boxes, and bearings are kept in the most perfect order, well-oiled and cleaned, so as at all times to be ready and fit for service. In the steam-engine also the same regularity and system of management are preserved, and the result is,—a ponderous piece of machinery, working with a degree of precision, at once the admiration of the employer as it is the pride of the engineer.

I would have all engines and machines kept clean and in

good order; and hence the advantage of our polished surfaces, and the mathematical exactitude with which the steam-engines of the present day are executed.

But in these constructions, we have other advantages besides those of appearance, or a desire to please the eye. A well-constructed machine, neatly executed, has a wonderful effect upon the mind of its keeper. It only requires a few months to accustom him to habits of cleanliness and order, and the time is probably not far distant when we may look forward to that important class of men, better instructed and better calculated for the discharge of their various duties than we can hope for in the present state of our educational resources. In conclusion, permit me to avail myself of the words of a distinguished writer, who, speaking of the steam-engine, says that—"*It is a thing stupendous alike for its force and flexibility; for the prodigious power which it can exert, and the ease, and precision, and ductility with which it can be varied, distributed, and applied. The trunk of an elephant, that can pick up a pin or rend an oak, is nothing to it. It can engrave a seal, and crush masses of obdurate metal like wax before it; draw out, without breaking, a thread as fine as gossamer, and lift a ship of war like a bauble in the air. It can embroider, and forge anchors, cut steel into ribands, and impel loaded vessels against the fury of the winds and waves.*" It can do all this and more since the eulogium here quoted was pronounced; and I look forward to the time, when still greater improvements will be effected in the action of the steam-engine and the use of steam.

APPENDIX.

APPENDIX I.

An Experimental Inquiry into the Strength of Wrought-Iron Plates and their Riveted Joints as applied to Ship-building and Vessels exposed to severe strains.*

The experiments herein recorded were instituted early in the spring of 1838, and before the close of the following winter most of them had been completed; owing however to a long series of professional engagements they have stood over (with the exception of some additions made in the following year) to the present time. The object of the inquiry was twofold—first, to ascertain by direct experiment the strength of wrought-iron plates and their riveted joints in their application as materials for ship-building; and secondly, to determine their relative value when used as a substitute for wood. On these two points it cannot be expected that our knowledge should be far advanced, as a very few years have elapsed since it was asserted that iron, from its high specific gravity, was not calculated for such a purpose, and that the greatest risk was likely to be incurred in attempting to construct vessels of what was then considered a doubtful material. Time has however proved the fallacy of these views, and I hope, in the following experiments, to show that the iron ship, when properly constructed, is not only more buoyant, but safer, and more durable than vessels built of the strongest English oak.

At the commencement of the experiments I felt desirous of conducting them upon a scale of such magnitude as would supply sound practical data, and at the same time establish a series of results calculated to ensure confidence as well as economy in the use of the material. My views were ably carried out by Mr. Hodgkinson, who conducted the expe-

* Philosophical Transactions, Part II. 1850, p. 677.

riments under my direction, and from whom I received valuable assistance.

In conducting the investigation I found it necessary to divide the subject into four distinct parts:—

1st. The strength of plates when torn asunder by a direct tensile strain in the direction of the fibre, and when torn asunder across it.

2ndly. On the strength of the joints of plates when united by rivets as compared with the plates themselves.

3rdly. On the resistance of plates to the force of compression, whether applied by a dead weight or by impact.

And lastly. On the strength and value of wrought-iron frames and ribs as applied to ships and other vessels*.

PART I.

At the commencement of iron ship-building, in which I took an active part, the absence of acknowledged facts relative to the strength and varied conditions under which the material was applied, was the principal reason which induced me to enter upon this inquiry. I have extended the investigation into the best methods of riveting, and the proportional strength of rivets, joints, &c., as compared with the plates and the uses for which they are intended. The latter is a practical and highly important inquiry, as great difference of opinion exists amongst engineers and others, as to the form, strength and proportions of rivets, and the joints of which they form an essential part. I therefore considered an experimental investigation much wanted, not only on account of its important practical bearing, but what was probably of equal value, in order to remove existing discrepancies and to establish a sounder principle of construction founded upon the unerring basis of experiment.

* Several important facts and improvements in the construction of iron ships have been ascertained since my experiments were made, but I apprehend none of them have tended in the least degree to diminish their value. Nor have they, to the best of my knowledge, been superseded by others of a more elaborate or more decisive character. It is true, that a series of interesting and important experiments have been made at the instance of the Admiralty on the effect of shot upon the sides of iron ships. At some of these experiments I had the honour to be present, and witnessed some curious and unexpected results.

The first series was conducted at the Arsenal, Woolwich, and subsequently others were made at Portsmouth. Both were important as respects the effect of shot upon wrought-iron plates, with enlarged and diminished charges of powder and at different velocities, but discouraging as regards the use of iron in the construction of ships of war. These experiments, however interesting in themselves, do not appear to be conclusive; and it is to be hoped that the apparent danger, indicated by the experiments, may yet be overcome, and the superiority as well as the greater security of the iron ship fully established.

From these considerations I bestowed increased attention upon the inquiry, and endeavoured to render it practically useful. Before detailing the experiments, it may be necessary to describe the apparatus by which the results were obtained.

The annexed drawings, Plate I., represent a side and end view of the apparatus used in the experiments. The large lever A was made of malleable iron and was fixed to the lower cross beam B (fig. 1) by a strong bolt O, which passed through it at B. At the top end of this bolt a preparation was made to receive the end of the lever, and by means of the screw-nut at *a*, the lever A was raised or lowered to suit the length of the plates to be experimented upon. Upon the top side of the beam, and under the gable wall of a building five stories high, were placed two cast-iron columns, D, D, which retained the beam B in its place and prevented it from rising when the lever was heavily loaded during the experiment. The frame E guided the end of the lever and the weight W, and close to the fulcrum were placed two wooden standards, F F, on which were fixed the cast-iron saddles receiving the cross bar G, from which the plates to be experimented upon were suspended. These plates were nearly all of the same form as shown at H, and were made narrower in the middle to ensure fracture in that part; the ends, as at *b*, *b*, had plates riveted to them on both sides, in order to strengthen them at those parts when attached to the bolts and shackle under strain.

The specimens thus prepared were suspended by the cross bolts *i*, *i*, and resting upon the standards were torn asunder by weights suspended from the large beam, as exhibited in the Plate.

In addition to the large weight W, a strong scale was attached to the extreme end of the lever at I, for the purpose of increasing the weights when required in the larger description of experiments, and by the application of a pair of blocks and the windlass K, the load was removed, and the changes produced upon the plates were by these means carefully determined.

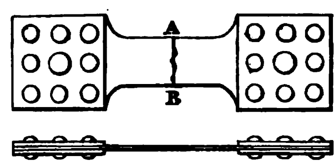
The following data respecting the weight W, lever, shackle, &c., are taken from the actual weights from which the calculations are made:—

		lbs.
W.	The weight with its carriage	2552
A.	The weight of the beam	1070
2 A.	The weight of the beam	2140
3 A.	The weight of the beam	3210
K.	Shackle	24
4 K.	Shackle	96
6 K.	Shackle	144

Experiments to ascertain the Strength of Plates, &c.

In the following experiments all the plates were of uniform thickness, and of the form exhibited in fig. 2 in the column of remarks; the ends had plates riveted to them on both sides to render them inflexible; they had holes, 0, 0, bored through them perpendicular to the plate, in order to connect it by bolts, with the apparatus for tearing it asunder in the part A B, which was made narrower than the rest. The centres of the holes 0, 0 were in a direct line through the middle between A and B*.

TABLE I. Strength of Plates.—Low Moor Yorkshire Iron.

No. of experiments.	Description of plate and dimensions in the middle.	Weight laid on in lbs.	Reduced dimensions in middle of plate through weights laid on.	Breaking weight in lbs.	Mean breaking weight in lbs.
1.	Drawn in the direction of the fibre. Area of section in the middle 2·00 × ·22 = ·44 in.	24,043 25,531	1·96 × ·21 1·89 × ·19	 25,531	
2.	....	23,571 24,747	Reduced. 1·93 × ·18	 24,747	 25,400, or 25·77 tons per square inch.
3.	....	25,923	1·94 × ·18	25,923	
Fig. 2. Plan and section of the plates, the line AB being that of the fracture. *Remarks.*—All the plates were laminated as if formed of three or more plates, the external ones being thinner than the internal ones†. In the last experiment there was a disunion between the lamina which admitted the point of a penknife.					
4.	Same iron drawn across the fibre. Area of section 2·00 × ·22 = ·44 in.	23,179 24,355 25,923 27,099	Altered. 1·99 × ·215 .... 2·2 × ·19	 27,099	 27,099, or 27·49 tons per square inch.
Remarks.—This, it will be seen, did not break at the narrowest place.					

* For the appearance of the fractures see Plate II.

† Nearly the whole of the plates manufactured in this country are laminated, owing to the manner in which the shingles are formed, by piling a number of flat bars one upon another, which are made larger or smaller according as the plate may be required heavier or lighter.

TABLE II. Strength of Plates.—Low Moor Yorkshire Iron.

No. of experiments.	Description of plate and dimensions in the middle.	Weight laid on in lbs.	Reduced dimensions in middle of plate through weights laid on.	Breaking weight in lbs.	Mean breaking weight in lbs.
5.	Same iron as in Table I., drawn across the fibre. Area of section $2{\cdot}00 \times {\cdot}22 = {\cdot}44$ in.	24,355 26,315	Stretching. $21{\cdot}5 \times {\cdot}20$	26,315	
6.	....	23,571	$2{\cdot}25 \times {\cdot}20$	23,571	25,662, or 26·037 tons per square inch.

Remarks.—The form and size of specimen as before, fig. 2.
In these experiments it was observed, as in No. 4. in the preceding Table, that the plate did not break at the narrowest part; a circumstance the more anomalous, as there did not appear to be anything in the apparatus to cause it.

No. of experiments.	Description of plate and dimensions in the middle.	Weight laid on in lbs.	Reduced dimensions in middle of plate through weights laid on.	Breaking weight in lbs.	Mean breaking weight in lbs.
7.	Same iron, thicker plates, drawn in direction of fibre. Area of section $2{\cdot}00 \times {\cdot}26 = {\cdot}52$ in.	27,099	Thickness ·25	27,099	
	....	25,923	$1{\cdot}96 \times {\cdot}24$	25,923	26,511, or 22·76 tons per square inch.

Remarks.—Very uniform in texture.
The fracture of this specimen showed a great want of regularity; about one-third of the area had the appearance of steel. All the other plates appeared to be uniform, but laminated, as mentioned before.

The results obtained from the Low Moor plates in the preceding Tables give fair indications of their strength. It will be observed, on comparing the mean of the breaking weights in this case with the experiments of Brown and Telford, that there is a very slight difference between the strength of plates and bar iron.

Taking the results of Captain Brown, we have in eight experiments on Swedish, Welsh and Russian iron, 25 tons as a mean of the breaking weight when reduced to an inch square.

In Mr. Telford's experiments on Swedish, Welsh, Staffordshire and faggoted iron, the mean breaking weight obtained from nine different bars was $29\frac{1}{4}$ tons to the square inch. The comparison will then be—

$$\left.\begin{array}{l}\text{Captain Brown's experiments, 25 tons to the square inch} \ldots\\ \text{Minord and Desames' experiments, 25 tons to the square inch}\\ \text{Mr. Telford's experiments, } 29\tfrac{1}{4} \text{ tons to the square inch} \ldots\end{array}\right\}\begin{array}{l}\text{Mean}\\ 26{\cdot}41 \text{ tons.}\end{array}$$

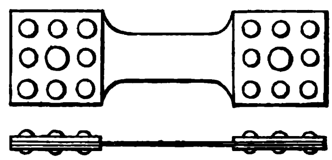
Yorkshire plates' experiments, $24\frac{1}{2}$ tons to the square inch.

Making the strength of plates to that of bars as $24{\cdot}5 : 26{\cdot}4$, being a comparatively small difference in their respective powers to resist a tensile force.

TABLE III. Strength of Plates.—Derbyshire Iron.

No. of experiments.	Description of plate and dimensions in the middle.	Weight laid on in lbs.	Reduced dimensions in middle of plate through weights laid on.	Breaking weight in lbs.	Mean breaking weight in lbs.
9.	Drawn in the direction of the fibre. Area of section 2·00×·28in. (Mean 2·00×2·85=·57)	21,219 28,667	Stretched. 2·00×·27	28,667	
10.	2·00×·29in.	21,219 22,789 26,707	Sinking. Sinking. 2·15×·27	26,707	27,687, or 21·68 tons per square inch.

Remarks.—Form of specimen the same as shown in Table I. fig. 2.
Exp. 10. There was a stripe resembling steel across the fracture near one side.



No. of experiments.	Description of plate and dimensions in the middle.	Weight laid on in lbs.	Reduced dimensions in middle of plate through weights laid on.	Breaking weight in lbs.	Mean breaking weight in lbs.
11.	Plates drawn across the fibre. Area of section 2·00×·28=·56 in.	22,395 23,179	Stretching. Thickness ·27	23,179	
12.	2·00×·28=·56 in.	24,747	2·00×·28	24,747	23,963, or 18·65 tons per square inch.

Remarks.—Exp. 11. In the broken surface there seemed to be a stratum of steel, the rest was laminated but imperfectly.
Exp. 12. Short streaks of steel in fractured surface.

If we compare the results in the Derbyshire plates with those in the preceding Tables, we have in the mean of four experiments a ratio of 20·165 : 24·850, or 5 to 6 nearly.

Again, by comparing the same plates with the mean strength of bars reduced to an inch square, the difference will be as 20 to 26, being an excess of 6 tons in favour of the bars.

TABLE IV. Strength of Plates.—Shropshire Iron.

13.	Drawn in the direction of the fibre. Area of section 2·00×·265=·53in.	......	....	28,275	
14.	....	......	....	25,923	27,099 or 22·826 tons per square inch.

Remarks.—Form of specimen the same as shown in Table I. fig. 2.
In the first experiment the fracture showed an iron very uniform, except a few bright spots like steel.
Experiment 2. Appearance of fracture as before, but a crack up the middle showed that the plate was formed of two plates of equal thickness, not well united.

TABLE IV. (*continued.*)

No. of experiments.	Description of plate and dimensions in the middle.	Weight laid on in lbs.	Reduced dimensions in middle of plate through weights laid on.	Breaking weight in lbs.	Mean breaking weight in lbs.
	Plates of the same iron drawn across the fibre.				
15.	2·00 × ·265 = ·53 in.	......	....	26,315	26,119, or 22 tons per square inch.
16.	....	......	....	25,923	

Remarks.—Fracture as before, with a laminated diversion, as in last experiment.

The Shropshire iron gives better indications of strength than those obtained from the Derbyshire plates; the mean breaking weights in the last Table being 22·41 tons. From the Yorkshire plates we have a mean breaking weight of 24·85 tons, exhibiting a difference of $2\frac{1}{2}$ tons in favour of the Yorkshire iron, and 2 tons or about $\frac{1}{10}$th greater than the Derbyshire.

TABLE V. Strength of Plates.—Staffordshire Iron.

	Drawn in the direction of the fibre.				
17.	2·00 × ·26 = ·52 in.	......	....	23,571	22,787, or 19·563 tons per square inch.
18.	....	......	....	22,003	

Remarks.—Form of specimen the same as before, fig. 2.
Fracture dark grey colour, very similar to that from the four preceding plates. It had however a few specks of bright matter in it, and was without any laminated appearance.

	Plates of the same iron drawn across the fibre.				
19.	Area of section 2·00 × ·265 = ·53 in.	......	....	24,335	24,943, or 21·01 tons per square inch.
20.	....	23·571	The thickness ·26	25,531	

Remarks.—Irregular in texture, air-bubbles in fractured surface, with bright crystallized matter like steel.
This iron has much of the same irregularity as the Derbyshire iron.
Surface of fracture showed the iron to be very irregular, one-half being bright matter like steel.

On comparing the strengths of the different irons, it appears that the Derbyshire and Staffordshire plates are nearly equal, the former indicating 20·165 tons as the mean of the breaking weight per square inch, and the latter, as in the preceding Table, 20·28 tons per square inch. The same comparison further applies to the above and those made on the Derbyshire plates in Table III.

Taking therefore the results as derived from these experiments, it will be observed, that in every instance little or no difference appears to exist in the resisting powers of plates, whether drawn in the direction of the fibre or across it. This fact is clearly established by the following comparison, which evidently shows, that in whatever direction the plates are torn asunder, their strength is nearly the same.

	Mean breaking weight in the direction of the fibre, in tons per square inch.	Mean breaking weight across the fibre, in tons per square inch.
Yorkshire plates	25·770	27·490
Yorkshire plates	22·760	26·037
Derbyshire plates	21·680	18·650
Shropshire plates	22·826	22·000
Staffordshire plates	19·563	21·010
Mean	22·519	23·037

Or as 22·5 : 23·0, equal to about $\frac{1}{45}$ in favour of those torn across the fibre *.

From the above it is satisfactory to know, so far as regards uniformity in the strength of plates, that the liability to rupture is as great when drawn in one direction as in the other; and it is not improbable that the same property would be exhibited, and the same resistance maintained, if the plates were drawn in any particular direction obliquely across their fibrous or laminated structure.

In order however to establish the relative powers of resistance in plates of rolled iron, I have endeavoured to tabulate the results, as derived from the preceding experiments, in such form as will indicate their respective values, and place them in comparison with each other, and also with those made on bars by Telford and Brown. The comparisons are made from the Yorkshire plates, as producing the best results; and conceiving them to be a fair average of the strength of rolled iron, I have selected them as the standard of comparison.

* In some experiments by Navier upon the strengths of plates of wrought iron, both in the direction of the fibre and perpendicular to it, he found them as 40·8 to 36·4. The new methods of piling the rough bars before rolling may however account for the difference, and in a great measure determines the strength of the plate. In this country the process of piling is by equal layers of flat bars at right angles to each other, which produces great uniformity of strength and texture in the manufacture. At other places there is sometimes a difference in the mode of piling, which varies the texture of the plate, and also the strength of the layers is greater in one direction than another.

Comparative results of rolled iron as derived from experiment, the Yorkshire plates being unity.

Names of Iron.	No. of experiments.	Mean breaking weight in tons per square inch.	Mean breaking weight in tons per square inch.	Ratio of the strength of plates drawn in the direction of the fibre, and across it. Also of rolled and faggoted bars drawn in the direction of the fibre.
Yorkshire plates	8	25·514	....	
Derbyshire plates......	4	....	20·160	1 : 0·7882
Shropshire plates	4	....	22·413	1 : 0·8789
Staffordshire plates ...	4	....	20·264	1 : 0·7946
Mean......	...	25·514	20·945	1 : 0·8209
From Mr. Telford and Captain Brown's experiments on bars...	...	....	26·41	1 : 1·0351

Here it will be observed that the difference between the strength of the Low Moor plates in their resistance to a tensile strain, when compared with bar iron, is inconsiderable; but taking the mean of the other irons, viz. the Derbyshire, Shropshire and Staffordshire, there is a falling off in the strength of about 21 per cent., the ratio being in favour of bar iron as 1·035 : ·8209.

In treating of the strength of iron, it may be useful to compare the foregoing experiments on the tensile strength of plates with those of a similar description on timber. On this subject I feel the more desirous of establishing a comparison, as the two kinds of material are now applied to similar purposes, such as ship-building and other constructions, and the question becomes every day more important as to which of the two materials is the best. There is every reason to believe that the advocates of improvement would arrange themselves on the side of iron, and those for the "wooden walls" would be equally zealous on that of timber. This is however a question which time and experience alone can determine, and conceiving that our knowledge of the properties of iron, as a material for ship-building, is far from perfect, we may safely leave its final decision to the evidence of experimental research, and a more extended application of its practical results.

When we attempt a comparison of the value of one material, in its application to a specific purpose, with that of another material similarly applied, the comparison is only correct when the two materials are placed in juxtaposition, or when they are contrasted under the same circumstances as to the trials and tests to which they are respectively subjected. Now in this comparison I am fortunate in having before me the able experiments of Musschenbrock, Buffon, and those of a more recent date on direct cohesion by Professor Barlow of Woolwich. I have selected from

the experiments of the latter those which appear to approach most nearly to the present inquiry; and impressed with the conviction of their having been carefully conducted and being from English timber, I attach the greatest value to them.

According to Musschenbrock's, the strengths of direct cohesion per square inch of the following kinds of timber are as follows:—

	lbs.		lbs.
Locust-tree	20,100	Pomegranate	9750
Locust-tree	18,500	Lemon	9250
Beech and oak	17,300	Tamarind	8750
Orange	15,500	Fir	8330
Alder	13,900	Walnut	8130
Elm	13,200	Pitch pine	7630
Mulberry	12,500	Quince	6750
Willow	12,500	Cyprus	6000
Ash	12,500	Poplar	5500
Plum	11,800	Cedar	4880
Elder	10,000		

From Barlow the strengths are,—

	lbs.		lbs.
Box	20,000	Beech	11,500
Ash	17,000	Oak	10,000
Teak	15,000	Pear	9800
Fir	12,000	Mahogany	8000

Mr. Barlow, in adverting to the experiments of Musschenbrock, observes, that some of them differ considerably from his own, a circumstance probably not difficult to account for, as the different degrees of dryness have a great effect upon the strength of timber *.

Dr. Robinson, in speaking of the experiments of Musschenbrock, states, that we may presume they were carefully made and faithfully narrated, but they were made on such small specimens, that the unavoidable natural inequalities of growth or texture produced irregularities in the results which have too great a proportion to the whole quantities observed. It is for the same reason that I give preference to Mr. Barlow's results, as he observes, "that the experiments from which they are drawn were made with every possible care which the delicacy of the operation would admit." Assuming therefore that Barlow is correct, and taking the mean strength

* It has been shown by Mr. Hodgkinson, that timber, when wet, will be crushed by a force less than one-half of what would take to crush it when dry. It therefore follows that much depends upon the samples selected and the way in which the timber has been seasoned.

of iron plates, as given in the preceding Tables, at 49,656 lbs. to the square inch, or calling it 50,000 lbs., and the resistance of the direct cohesion of different kinds of timber as given by Mr. Barlow, the following ratio of strengths will be obtained:—

	Timber lbs.	:	Iron. lbs.	Ratio, taking timber as unity.
Ash	17,000	:	50,000,	or as 1 : 2·94
Teak	15,000	:	50,000,	or as 1 : 3·33
Fir	12,000	:	50,000,	or as 1 : 4·16
Beech	11,500	:	50,000,	or as 1 : 4·34
Oak	10,000	:	50,000,	or as 1 : 5·00

Hence it appears that the direct cohesion of iron plates is five times greater than oak; or in other words, their powers of resistance to a force applied to tear them asunder is as 5 to 1, making an iron plate $\frac{1}{2}$ inch thick equal to an oak plank of $2\frac{1}{2}$ inches thick. In the teak wood and fir specimens, which exhibit greater resisting powers, nearly the same rule will apply, and thinner planks, as regards the tensile strength, would answer the purpose. This is a circumstance which may be applicable to teak wood, but unfavourable to fir when viewed as a building material exposed to a great variety of strains, or when used for sheathing and similar purposes in the art of ship-building. The teak wood being timber of greater density and of higher specific gravity, is better calculated to resist shocks than a tough fibrous substance of a soft and spongy nature, such as fir.

On this subject it should however be noticed, that whatever material is used for covering the ribs of vessels, it should be strong and elastic, in order to resist not only the force of direct tension, but that of lateral and compressed action. In a ship at sea these forces are strikingly exemplified, and that under circumstances embarrassing as well to the practical builder as the man of science.

Remarks on the foregoing experiments.

Having determined the strength of iron plates when drawn in the direction of the fibre as well as across it, and having compared the results with experiments of a similar character on timber, it may be useful to offer a few general observations on the question now under consideration.

Dr. Robinson, in his article on the strength of materials *, when discussing the nature of a stretching force applied to materials, observes, "that in pulling a body asunder the force of cohesion is directly opposed

* Encyclopædia Britannica.

with very little modification of its action; that all parts are equally stretched, and the strain in every transverse section is the same in every part of that section." From this it would appear, that a body of a homogeneous texture will have the cohesion of its parts equal, and since every part is equally stretched, it follows that the particles will be drawn to equal distances, and the forces thus exerted must be equal. Now if this were true, the application of an external force to a body might be increased to such an extent as not only to separate the parts furthest asunder, but ultimately to destroy the cohesion of all the particles *at once*, a circumstance under which instantaneous rupture would follow as a result. These views are however not borne out by facts, as the experiments of Mr. Hodgkinson on iron wire show that the same iron may be torn asunder many times in succession without impairing its strength*; and some recent experiments at the Royal Dockyard, Woolwich, clearly show, that an iron bar may be stretched until its transverse section is considerably reduced and ultimately broken without injury to its tensile strength. Nay, more, the same iron (so elongated), when again submitted to experiment, exhibited increased strength, and continued to increase, under certain limitations, beyond the bearing powers of the same bar in its original form †. That all the parts of a body "subjected to a tensile strain are equally stretched" is therefore questionable. Bodies vary considerably in their powers of resistance, and exhibit peculiar properties of cohesion under the influence of forces calculated to tear them asunder. Fibrous substances, for instance, such as ropes and some kinds of timber having their fibres twisted, are enabled to resist tension under the influence of considerable elongation without impairing their ultimate strength. Many of the fibres are stretched, but only to the extent of bringing the others to bear upon the load, which done, their united force constitutes the maximum of resistance to a tensile strain.

Other bodies of less ductility and more of a crystalline structure, such as cast iron, stone, glass, &c., seem to be subject to the same law. In these cases it seldom happens that the whole of the particles are brought into action at once, as much depends upon the conditions of the body, the unequal state of tension of its parts, and the strain which some of the particles must sustain before the others receive their due portion of the load. Should the non-resisting particles be within the limits of elongation of the other particles, the body will then have attained its maximum power of resistance; but in the event of rupture to any of the resisting particles, the cohesive force of the body is thereby

* Manchester Memoirs, vol. v.

† I am indebted to Mr. Thomas Loyd of the Admiralty for a series of interesting results on this subject.

reduced, and that to the extent of the injury sustained by the fractured parts.

"There are however," as Dr. Robinson truly observes, "immense varieties in the structure and composition of bodies which lead to important facts, and prove that the absolute cohesion of all bodies, whatever be their texture, is proportional to the areas of their sections." Undoubtedly this is the case in bodies having an uniform texture with straight fibres, and hence it follows that the absolute strength of a body, resisting a tensile strain, will be as the area of its section.

The peculiar nature of the material combining a crystalline as well as a fibrous structure has led to these observations. In some instances the specimens experimented upon exhibited an almost distinct fibrous texture, and in others a clearly developed crystalline structure *. At other times some of the specimens were of a mixed kind, with the crystalline and fibrous forms united; the fracture having a laminated appearance, with the crystalline parts closely bound on each side by layers of the fibrous structure. These varieties are probably produced in the manufacture, and may be easily effected either by the mode of "piling" the layers of bars which form the plate, or from the unequal temperature of the parts as they pass through the rolls. But whichever way they are produced, it is evident, from the experiments, that the fractures gave, in most cases, indications of an unequal and varied texture.

In the foregoing experiments, and also in those which follow, great attention was paid to the appearance of the fracture, in order to ascertain the structure of the plate, and to determine how far it could be depended upon in its application to the varied purposes for which it was intended.

These appearances are all shown in the drawings appended to the experiments, and to which I beg to refer.

PART II.

On the Strength of Iron Plates united by Rivets, and the best mode of Riveting.

The extensive and almost innumerable uses to which iron is applied, constitute one of the most important features in the improvements of civilized life. It contributes to the domestic comforts and commercial greatness of the country, and from its cheapness, strength and power of being moulded, rolled and forged into almost every shape, it is not only the strongest, but in many respects the most eligible material for the

* See the fractured parts of the different specimens, Plate II.

construction of vessels exposed to severe strain. Large vessels composed of iron plates, such as steam-boilers, cisterns, ships, &c., cannot however be formed upon the anvil or the rolling-mill. They are constructed of many pieces, and these pieces have to be joined together in such a manner as to ensure the requisite strength and effect all the requirements of sound construction. This operation is called riveting, and although practically understood, it has not, to my knowledge, on any previous occasion, received that attention which the importance of the subject demands.

Up to the present time* nothing of consequence has been done to improve or enhance the value of this process. We possess no facts or experiments calculated to establish principles sufficient to guide our operations in effecting constructions of this kind, on which the lives of the public as well as the property of individuals depend. In fact, such has been our ignorance of the relative strength of plates and their riveted joints, that until the commencement of the present inquiry the subject was considered of scarcely sufficient importance to merit attention. Even now, it is by many assumed that a well-riveted joint is stronger than the plate itself, and a number of persons, judging from appearances alone, concur in that opinion. Now this is a great mistake, and although the double thickness of the joint indicates increased strength, it is nevertheless much weaker than the solid plate, a circumstance of some importance, as we hope to show in the following experiments.

It would probably be superfluous to offer any lengthened description of the principle upon which wrought-iron plates are united together; riveting is so familiar to every person in this country, that it might appear a work of supererogation to attempt it; and, assuming that the usual method of riveting by hammers to be generally known, we shall proceed to describe another method by machinery which effects the same object in considerably less time and at less cost, and completes the union of the plates with much greater perfection than could possibly be done by the hand. In hand-riveting it will be observed, that the tightness of the joint and the soundness of the work depends upon the skill and also upon the will of the workman, or those who undertake to form the joint and close the rivets. In the machine-riveting neither the will nor the hand of man has anything to do with it, the machine closes the joint and forms the rivet with an unerring precision, and in no instance can imperfect work be accomplished so long as the rivets are heated to the extent compressible by the machine. This property of unvarying soundness in the work constitutes the superiority of the machine over the

* 1838, when these observations were written.

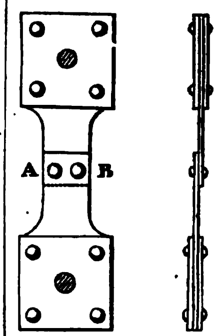
hand-riveting. The machine produces much sounder work, as the time occupied in the hand process allows the rivet to cool, and thus by destroying its ductility, the rivet is imperfectly closed, and hence follow the defects of leaky rivets and imperfect joints. It is evident that an instrument, such as the riveting-machine, having sufficient force to compress the rivet at once, or within an almost infinitely short period of time, must obviate, if not entirely remedy, these evils, as the force of compression being nearly instantaneous, the heads on both sides cannot be formed until the body of the rivet is squeezed tight into the hole; and in every case (even where the holes are not exactly straight) the compressed rivets are never loose, but fill the holes with the same degree of tightness as if placed directly opposite to each other. If, for example, we take a circular boiler, such as represented at A*, Plate III. fig. 3, and having all the perforations made and the plates attached to each other by temporary bolts and suspended over the machine in the position as shown at A, and having brought the holes in a line with the die marked *i*, *k*, the machine then is set to work, and by means of the cam or excentric raising the pulley of the elbow-joint C, the die *k* is advanced against the fixed die *i* in the wrought-iron stem, and the rivet is compressed into the required form with an increasing force as the die advances which gives the "nip," or greatest pressure, at the required time, namely, at the closing of the rivet.

From this description it will appear that a very limited portion of time is occupied in the process, and as twelve rivets can be inserted and finished by the machine in a minute, it follows, from the rapidity of the operation and the absence of hammering, that the ductility of the rivets is retained, and their subsequent contraction upon the plate renders the joint perfectly tight and the rivets sound in every respect. Under all the circumstances the machine-riveting is preferable to that executed by the hammer; it saves much time and labour, and that in proportion of 12 to 1, when compared to a long series of impacts applied by the hammer.

Having described the process of uniting wrought-iron plates by rivets, it may be of some importance to know the value of joints thus formed as regards their strength when compared with the plates themselves. To attain this object, and satisfactorily to determine their powers of resistance to a tensile strain, a great variety of joints were made, and having prepared the different specimens with the utmost care and attention, they were submitted to the test of experiment as follows:—

* The plan represents the machine in the act of riveting the corners of a square cistern or a locomotive fire-box.

Table VI. Strength of Riveted Plates.—Yorkshire Iron*.

No. of exp.	Description of plates and mode of riveting.	Weight laid on in lbs.	Changes produced by weights.	Breaking weight in lbs.	Form of specimen and mode of fracture.
21.	Plates ·22 inches thick, overlap joints, two rivets half-inch diameter, lap 1¼ inch, AB = 3 inches, riveted by the patent machine	......	....	20,011 } Mean 20,127	Fig. 4. 
22.	Same as last, area ·44 in.	......	....	18,667	
23.	....	......	....	21,703	
	Remarks.—Exp. 21. Torn across at the rivet-holes. Exp. 22. Rivet-holes torn out. Exp. 23. Rivet-holes torn out.				
24.	Plates as before, riveted by the hammer, the rivets half-inch diameter, being of the usual length, but rather shorter than those used for the machine	14,839	....	16,115 } Mean 16,107	Specimen same as before, fig. 4.
25.	....	15,843	Plates bent.	16,099	
	Remarks.—Exp. 24. Rivet-heads broke off and the plate torn across them in consequence. Exp. 25. Rivet-heads cracked across and rivet-holes torn out.				
26.	Plates same as before and riveted by the hammer, with half-inch rivets, the rivets being a little longer and 2 inches lap	14,839	Plates bent nearly into a direct line with straining force.	17,833 } Mean 18,982	Specimen same as before, fig. 4.
27.	....	14,839	....	20,131	
	Remarks.—Here the rivets were the same length as the machine rivets, experiments 1, 2, 3, and were worked with great care on both sides. Exp. 26. Both rivet-heads broken and the plate torn across them. Exp. 27. Torn across at rivet-holes, and one rivet-head split.				

* The nature and appearance of the fractures of all the irons and their riveted joints are shown in Plate IV.

TABLE VI. (continued).

No. of exp.	Description of plates and mode of riveting.	Weight laid on in lbs.	Changes produced by weights.	Breaking weight in lbs.		Form of specimen and mode of fracture.
28.	Plates same as before, lap 2 inches, and the rivets the same as in the last experiment, but riveted by the machine	14,839	Plates bent into a direct line by the straining force...	19,123	Mean 19,147	Specimen same as before, fig. 4.
29.	....	18,667	Joint apparently sound.	19,171		

Remarks.—Exp. 28. Both rivets cracked across, metal torn across the rivet-holes.
Exp. 29. Torn across at the rivet-holes, both rivets slightly cracked near the head.

The plates used in the foregoing experiments are of Yorkshire iron, the same as those employed in Tables I. and II. The specimens were prepared in the same manner and of the same thickness, but 1 inch wider at the joint. This was done in order to retain sufficient metal round the rivet-holes, making the breadth of the plate the same after the rivet-holes were punched out as that of the plates torn asunder in the preceding experiments. In all these experiments only two half-inch rivets were used in the breadth of the plate. The lap was however increased, after the three first experiments, from $1\frac{1}{2}$ to 2 inches, to give greater strength in the longitudinal line of the plate and to prevent the metal tearing in that direction. This precaution was found necessary, as the metal gave indications of weakness in consequence of the lap being rather narrow. Another reason for enlarging the lap was a desire at the commencement to begin with the least possible quantity, and by direct experiment to ascertain the maximum distance which the plates should overlap each other in the joints, and to determine the strongest and best form of uniting them. To these points every attention was given, for the purpose of collecting the facts on which are founded the tabulated results on that part of the subject which treats of the comparative dimensions of rivets and extent of the lap in reference to the thickness of the plates. In this department of the inquiry will be found the depth of lap, diameter and length of rivets, and the distances of holes for nearly every description of joint; also the thickness of the plate, with a column of strengths as deduced from the experiments.

If we examine the nature of the fracture in the foregoing experiments, it will be found that the machine-riveting is superior to that done by the hammer; the mean of the three first experiments being to the mean of the fourth and fifth as 5 : 4. In the eighth and ninth the strengths are nearly the same.

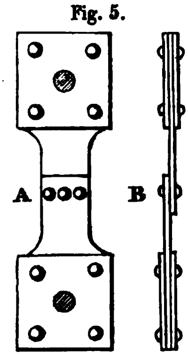
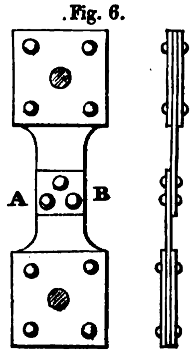
On comparing the strength of plates with their riveted joints, it will be necessary to examine the sectional areas taken in a line through the rivet-holes with the section of the plates themselves. It is perfectly obvious, that in perforating a line of holes along the edge of a plate, we must reduce its strength; and it is also clear, that the plate so perforated, will be to the plate itself nearly, as the areas of their respective sections, with a small deduction for the irregularities of the pressure of the rivets upon the plate; or in other words, the joint will be reduced in strength somewhat more than the ratio of its section, through that line, to the solid section of the plate. For example, suppose two plates, each 2 feet wide and three-eighths of an inch thick, to be riveted together with ten $\frac{3}{4}$-inch rivets. It is evident that out of 2 feet, the length of the joint, the strength of the plates is reduced by perforation to the extent of $7\frac{1}{2}$ inches; and here the strength of the plates will be to that of the joint as 9 : 6·187, which is nearly the same as the respective areas of the solid plate, and that through the rivet-holes, namely, as 24 : 16·5. From these facts it is evident that the rivets cannot add to the strength of the plates, their object being to keep the two surfaces of the lap in contact, and being headed on both sides, the plates are brought into very close union by the contraction or cooling of the rivets after they are closed. It may be said that the pressure or adhesion of the two surfaces of the plates would add to the strength; but this is not found to be the case, to any great extent, as in almost every instance the experiments indicate the resistance to be in the ratio of their sectional areas, or nearly so.

If we take the ultimate strength of the Yorkshire plates in Tables I. and II., it will be found that the mean breaking weight of eight specimens, each with a sectional area of ·46 inch, is 26,168, and the strength of the single joint*, of the same description of plates with an area of ·44 inch, is 18,591; this reduced gives the ratio of the strength as 25,030 : 18,591, or as 1 : ·742, the comparative strength of a single riveted plate of equal area through the line of the rivets. It will be observed that in this comparison the areas of the sections are nearly equal, and consequently there is a difference in strength between the solid part of the plate and that part where the perforations have been made of 32 per cent. The difference is considerable, but it probably arises from the narrowness of the specimen and the lateral strain induced by the position of the rivet, and the bending upwards of the end of the plates. From these facts I would infer that single riveting is weaker, and probably the loss of strength in this description of joint, including loss

* I use the term single joint to distinguish it from the double riveted joint, which will be treated of hereafter.

caused by the rivet-holes, is not less, under ordinary circumstances, than 40 per cent.

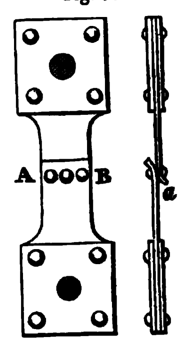
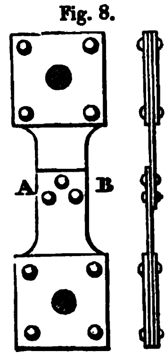
TABLE VII. Strength of riveted Plates.

No. of exp.	Description of plates and mode of riveting.	Weight laid on in lbs.	Changes produced by weight.	Breaking weight in lbs.	Form of specimen and mode of fracture.
30.	Plates 22 inches thick, with three rivets, each ⅜ inch diameter, AB 3 inches, lap 1½ inch, area through rivet-holes ·4125	14,839	Bent into a straight line.	16,603	Fig. 5. 
Remarks.—The plates were sound, but two of the rivets were cut directly across. Rivets too weak.					
31.	Plates the same as before, overlap joints differing from the last in having three rivets ½ inch diameter, forming an isosceles triangle, AB 3 inches	18,667	Joint apparently sound.	22,699	Fig. 6. 
		20,683	Single rivet slightly opened.		
		22,027	The other two rivets quite tight.	Mean 23,035	
32.	Same as before	18,667	Separation at end of plate, single rivet slightly opened.		
		22,027	....		
		23,035	Slightly drawn at the rivets......	23,371	
Remarks.—Exp. 31. With the first weight the plates became bent, so as to be in a direct line with the straining force. Exp. 32. Tore across the two rivet-holes, in the direction AB. With 22,027 lbs. the single rivet seemed somewhat opened, but the other two seemed quite close. Plate tore across at the single rivet and one of the double ones. Rivets sound in this and the preceding experiment.					

In the first experiment the rivets (two in number) were evidently too weak, which caused them to shear directly across as if cut by a pair of scissors. In the next experiment the rivets were increased in number and size, which gave an excess of strength to the retaining power of the

rivets and caused the plate to tear. If we take the mean of the experiments as respects the area of the rivets to that of the plates, we find two half-inch rivets about the proportion, or the area of the rivets in the last experiments should have been ·4 inch, which is nearly equal to the area of the plate through the rivet-holes*.

TABLE VIII. Strength of riveted Plates.

No. of exp.	Description of plates and mode of riveting.	Weight laid on in lbs.	Changes produced by weight.	Breaking weight in lbs.	Form of specimen and mode of fracture.
33.	Plates same as before, ·22 inch thick, but wider, AB being 3½ inches, with three rivets ½ inch diameter, all in a line; lap 1¾ inch	18,667	Ends of plate much separated by bending.	19,675	Fig. 7. 
Remarks.—Though the ends of the plates were much separated, the light of a candle could not be seen through the line of the rivets. Plate torn across at the rivet-holes.					
34.	Thicker plates ·26 in. thick, in other respects the same as in experiments 31, 32, Table VII.; lap 3 inches; rivets ½ inch diameter	18,667 22,699	Ends of plate separated, joints apparently good. One plate much bent; joint apparently good.	23,707 } Mean 25,387	Fig. 8. 
35.	Plates the same as the last	21,019	One end separated so far as to exhibit the single rivet.	27,067 }	
Remarks.—Exp. 34. Tore across the two rivet-holes. Exp. 35. Tore across the two rivet-holes, where the breadth was 3½ inches.					

* Subsequent experiments made for ascertaining the strength of rivets (*vide* experiments on the strength of rivets for the Britannia and Conway Tubular Bridges) fully corroborate these views, namely, that riveted joints exposed to a tensile strain are directly, or nearly so, as their respective areas, or in other words, the collective areas of the rivets are equal to the sectional area of the plate taken through the line of the rivets.

Here the section of the rivets is to that of the plates, through the line of the rivets, in the ratio of ·58 to ·44; had they been equal, it is probable that fracture would have taken place as soon by the rivets shearing as through the plates.

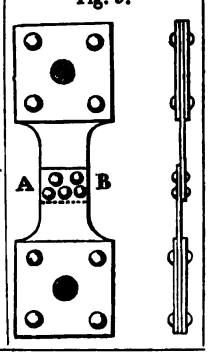
During the whole of the experiments on single riveted joints, it was observed that the ends of the plates under strain curled upwards on each side, and produced a diagonal strain upon the plates, which materially reduced the strength of the joint, as shown at *a* fig. 7.

This position gave an oblique direction to the forces, and caused the plate to break in some degree transversely through the rivet-holes. In order to obviate this defect, and prevent as much as possible a transverse strain upon the plates through the points in contact, the lap was increased and a third rivet introduced to keep down the ends of the plates.

The sketches in the 31st experiment, Table VII., and those in the 34th and 35th experiment, Table VIII., represent the form of joint, and the methods adopted for securing the plates in the direct line of the strain.

On comparing the breaking weights, it will be seen that the increased lap, with a rivet to keep down and retain the ends of the plates, gives a considerable accession of strength, and exhibits several important facts in connexion with the construction of vessels exposed to severe pressure. But this becomes more apparent in the forthcoming experiments on the double-riveted joints.

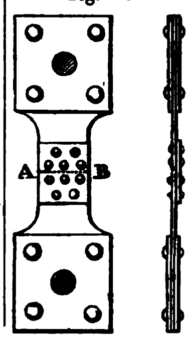
Table IX. Strength of riveted Plates.

No. of exp.	Description of plates and mode of riveting.	Weight laid on in lbs.	Changes produced by weight.	Breaking weight in lbs.	Form of specimen and mode of fracture.
36.	Double-riveted plates ·22 inch thick; overlap joints riveted with five rivets of ⅜ inch diameter each; lap 2 inches; AB = 3 inches in breadth ...	16,115	Plates bent in a right line between the points of tension.		Fig. 9. 
		21,715	Little or no alteration	24,043	
37.	Plates the same as before, except that AB = 2⅛ inches in breadth	18,667	Plates bent into right line, as before.	21,019	
				Mean 22,531	

Remarks.—Exp. 36. Torn right across at the three rivet-holes, all the rivets being sound after fracture.
Exp. 37. Broke as before; rivets all sound.

In these experiments, as in those in the preceding Table, the area of the rivets is in excess, and hence follows rupture through the plates.

TABLE X. Strength of riveted Plates, &c.

No. of exp.	Description of plates and mode of riveting.	Weight laid on in lbs.	Changes produced by weight.	Breaking weight in lbs.	Form of specimen and mode of fracture.
38.	"Jump Joints." Plates the same as before, both riveted to an extra plate of the same thickness laid on one side of them; lap of extra plate over each end 2 inches; each plate riveted by five rivets $\frac{3}{8}$ inch diameter; AB $=3\frac{1}{8}$ inches.	14,839	Bent into straight line.		Fig. 10. 
		19,627	All sound.		
		21,691	Rivets sound; plates much bent	23,371 Mean 23,707	
39.	Same as above ...	18,667	Bent nearly into a straight line.		
		22,699	Rivets sound; joint apparently good	24,043	

Remarks.—Exp. 38. Tore across the rivet-holes. Rivets sound after fracture.
Exp. 39. Tore across as before; one rivet-head crooked.

The same observations will apply to these experiments as to the last; the area of the rivets is in excess of that of the plates.

The system of double riveting exhibits several remarkable properties as regards strength, and the plates appear to retain their position under strain much better than single-riveted joints. These circumstances have induced a comparison of the results of the preceding experiments with those contained in Tables VII., VIII., IX. and X. The experiments in Tables VII. and VIII. give indications of increased strength by a slight enlargement of the lap and the introduction of a single rivet to keep down the end of the plate. In those experiments it was found that the additional rivet gave an increase of 26 per cent. over those obtained from the single rivets; a circumstance which suggested a further extension of the experiments, accompanied with a minute investigation of the parts, in order to ascertain their relative strengths, and the strongest form of joint.

The mean breaking weights of equal sections of single-riveted joints, as given in Table VI. and taken from nine experiments, are respectively as follows:—

$$\left.\begin{array}{r}\text{lbs.}\\ 20{,}127\\ 16{,}107\\ 18{,}982\\ 19{,}147\end{array}\right\}\text{Mean} \dots\ 18{,}590$$

giving a mean of 18,590 lbs. for the strength of single-riveted joints. Now in the second and third experiments, Table VII., with the rivets

inserted in the shape of an isosceles triangle (which in fact is double riveting), and of equal sections to the specimens in Table VI., the mean breaking weight is 23,035, which gives an excess of 4445, or a ratio of 10 : 8 in favour of the experiments recorded in Table VII.

In the experiments (Table X.), the area of the section, taken through the line of the rivet-holes, is ·44 inch, or precisely equal to the section of the specimens experimented upon in Table VI., in which the mean breaking weight is 18,590 lbs. In these experiments the breaking weight is 23,707 lbs., which is rather more than that in Table IX., where the material had a smaller section, but having its dimensions exactly corresponding with the proportions given above. It therefore follows that in plates jointed with single rivets, the ratio of the strength of the single rivets is to that of the double-riveted joints as 8 to 10, the latter being one-fourth stronger.

It has been ascertained that it required a weight of 23,707 lbs. to tear asunder double-riveted plates, $3\frac{1}{8}$ inches wide and ·22 inch thick, with a flush joint, having a plate on the back and held together by five $\frac{5}{8}$-inch rivets on each side; the quantity of metal between the holes, in a direct line across the plate, being $\cdot 2 \times \cdot 22 = \cdot 44$ inch, which is the same transverse section as those operated upon in the first Table.

Now if we take the mean breaking weights of the riveted joints in Tables X. and VI. and compare them with the section of the plate itself as given in Table I., the areas being the same, we have for the tensile strength of plates—

	Section of iron torn asunder.	lbs.
In Table I., solid plate	·44	25,400
In Table X., double-riveted joints	·44	23,707
In Table VI., single-riveted joints	·44	18,590

Assuming therefore the strength of the plates to be 1000, we have—

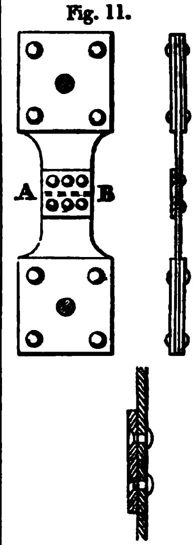
For the strength of plates of equal sections	1000
For the double-riveted joints	933
For the single-riveted joints	731

We may safely assume these ratios as the comparative values of jointed plates of equal sections when acted upon by a force calculated to tear them asunder.

The correct value of the plates, computed from a sectional area taken through the rivet-holes, will therefore be to their riveted joints as 100, 93 and 73, or in round numbers as 10, 9 and 7.

In addition to a loss of nearly one-tenth in the double-riveted joints, and three-tenths in the single ones, it will be observed that the strength of the plates is still further reduced by the quantity of iron punched out for the rivets.

TABLE XI. Single riveted Plates.

No. of exp.	Description of plates and mode of riveting.	Weight laid on in lbs.	Changes produced by weight.	Breaking weight in lbs.	Form of specimen and mode of fracture.
40.	Plates same as before, ·22 inch thick, with overlap joint and double rivets; countersunk on one side; AB = $3\frac{1}{8}$ inches; five rivets, each $\frac{5}{8}$ diameter	19,675	Plates bent in a right line; doubtful whether the joint would hold water ...	23,707	Fig. 11. 
41.	Plates the same strength, but different from the last in having only $\frac{5}{8}$-inch rivets all in a line; AB = $3\frac{1}{8}$ ins.	14,889	Plates bent into a right line with the fixing	16,351	
42.	Same as last, except in not having the rivet-holes countersunk; lap $1\frac{1}{8}$ inch; AB = $3\frac{1}{8}$ inches	14,889	Joint sound.........	16,351	

Remarks.—Exp. 40. By the word countersunk is understood a conical recess on one side of the plate to receive the head of the rivet, in order that it might not project beyond the surface of the plate. Tore across the three rivet-holes.

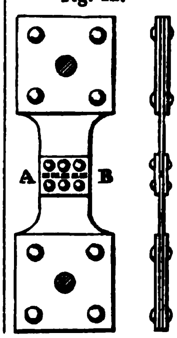
Exp. 41. In an unsuccessful experiment made before this upon plates precisely the same, and riveted in the same manner, they were torn across the rivet-holes in attempting to lay on 18,667 lbs. Plates tore across the rivet-holes.

Exp. 42. All the rivets on one side were cut in two in the middle, and the plates left sound.

The results in the two last experiments, in the above Table, are identical as to strength. In the first, with the countersunk rivets, the plates were torn asunder, and in the latter the rivets appear the weakest, owing to the increased sectional area of the plates, which in the preceding experiment was reduced by countersinking the rivets.

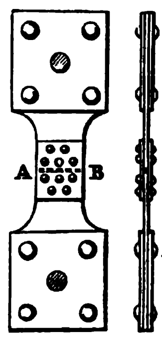
In both experiments it will be observed that the strengths of the rivets are proportional to the strengths of the plates, their powers of resistance being equal, or nearly so. In forty-one experiments the sectional area of the rivets was to that of the plates as ·340 to ·347, that is, the sections were nearly equal; and in forty-two experiments as ·34 to ·44, which accounts for the nature of the fracture in both cases.

TABLE XII. Strength of riveted Plates.

No. of exp.	Description of plates and mode of riveting.	Weight laid on in lbs.	Changes produced by weight.	Breaking weight in lbs.		Form of specimen and mode of fracture.
43.	Plates the same as before, their edges brought into contact, and each plate riveted by three rivets $\frac{5}{8}$ of an inch diameter, to a plate on each side of the joint, each external plate being half the thickness of the internal, or a little thicker; AB = $3\frac{1}{8}$ ins.	19,879	Sound; no alteration.			Fig. 12. 
		24,715	....	25,723	Mean 23,539	
44.	Plate same as last	....	....	21,355		

Remarks.—Exp. 43. Both side plates were torn across, and two of the rivets cut off. The sum of the thickness of the side plates was ·24 inch, the middle plates being ·22 inch thick. The middle plates were left sound.

Exp. 44. Second experiment broken as before, the two outside plates torn off; all the rest sound.

No. of exp.	Description of plates and mode of riveting.	Weight laid on in lbs.	Changes produced by weight.	Breaking weight in lbs.		Form of specimen and mode of fracture.
45.	Same as the last experiment, having thicker plates outside, each being ·15 inch thick	23,371	Joint good	24,715		Fig. 12 *a*. 
46.	Differing from the last only in having five rivets to each plate in double rows instead of three rivets $\frac{5}{8}$ diameter; AB = $3\frac{1}{8}$ inches...	23,371	Joint sound.			
		25,387	....	26,059	Mean 26,731	
47.	Same as the last ...	23,371	Joint sound			
		24,715	Slightly altered; joint good	27,403		

Remarks.—Exp. 45. Middle plate torn straight across the rivet-holes. All the rivets and both plates left sound.

Exp. 46. Both outside plates torn across at the three rivets.

Exp. 47. Outer plate sound; torn across the two rivet-holes. Rivets sound; inner plate only torn.

When the comparative merits of plates and their riveted joints were under consideration, it appeared desirable to repeat several of the experiments, particularly those which seemed to throw light upon their relative powers of resistance. I considered these experiments to be of importance, as they increased our knowledge, as respects the strength of the material, and also its properties in combination.

In ship-building these objects are of some value, as any reduction in the powers or parts of a vessel by imperfect construction, or misapplied material, might lead to serious error and even great risk to the safety of the ship.

Since the first use of iron for these objects, it has been the practice to countersink the heads of the rivets in order to present a smooth surface for the passage of the vessel through the water. This practice is in general use at my works at Millwall, and I believe the same methods are pursued at the establishment of Messrs. John Laird and Co., and others in different parts of the country. The introduction of this system of riveting caused a further extension of the experiments, in order to elucidate the various forms of joints given in the preceding Tables, and further to investigate the strength of the joint with a plate riveted on each side, which appears to be the strongest and best calculated to resist a tensile strain. This description of joint is seldom used in ship-building, but in order to render the experiments as perfect as possible, it will be necessary to consider it in this paper with others of equal importance and probably of more general use.

The system of countersinking the rivets is only used when smooth surfaces are required; under other circumstances their introduction would not be desirable, as they do not add to the strength of the joint, but to a certain extent reduce it. This reduction is not observable in the experiments, but the simple fact of sinking the head of the rivet into the plate and cutting out a greater portion of metal, must of necessity lessen its strength, and render it weaker than the plain joint with raised heads. This must appear evident from the fact of the sectionial area of the plate being diminished, and the consequent reduction of the heads of the rivets, which in this state are less able to sustain the effects of an oblique or transverse strain.

It is, however, satisfactory to observe that countersinking the heads of the rivets does not seriously injure the joint in its powers of resistance to a direct tensile force; but the rivets are liable to start when exposed to collisions or a strong impinging force, such as the sides of ships are frequently doomed to encounter.

On referring to experiments (Table XI.), the same results as to strength are obtained with the countersunk rivets as those with rounded heads; they are rather under the mean of the former experiments, but not more than is easily accounted for by the reduced section of the countersunk plates.

The joint with plates, riveted on each side, is seldom used, a circumstance which probably arises from its greater complexity of form and the danger which a treble thickness of plate would be subject to if used in

boilers or vessels exposed to the action of intense heat. It is also inadmissible in ship-building, as the smooth surface requires to be maintained, and the greatest care observed in the formation of the outer sheathing to lessen the resistance of every part of the hull immersed in the water. In other respects the double-riveted plate is a strong joint, and in every case, where great strength is required, it may be used with perfect safety.

It will be unnecessary to go through a further comparison of the experiments, as sufficient data have already been furnished to enable us to calculate the force per square inch, and to resolve the whole into a general summary exhibiting the relative strengths—1st, of the plates; 2ndly, of the single- and double-riveted joints; and lastly, the ratio of the strengths as deduced from the whole series of experiments.

General summary of Results as obtained from the foregoing Experiments.

	Cohesive strength of plates. Breaking weight in lbs. per square inch.	Strength of single-riveted joints of equal section to the plates, taken through the line of rivets. Breaking weight in lbs. per square inch.	Strength of double-riveted joints of equal section to the plates, taken through the line of rivets. Breaking weight in lbs. per square inch.
	57,724	45,743	52,352
	61,579	36,606	48,821
	58,322	43,141	58,286
	50,983	43,515	54,594
	51,130	40,249	53,879
	49,281	44,715	53,879
	43,805	37,161	
	47,062		
Mean	52,486	41,590	53,635

The relative strengths will therefore be,—

For the plate	1000
Double-riveted joint . . .	1021
Single-riveted joint	791

From the above, it will be seen that the single-riveted joints have lost one-fifth of the actual strength of the plates, whilst the double-riveted have retained their resisting powers unimpaired. These are important and convincing proofs of the superior value of the double joint, and in all cases where strength is required this description of joint should never be omitted.

On referring to the experiments contained in the separate tables, there will be found a striking coincidence in the facts tending to establish the principle of double riveting as superior in every respect to the general practice now in use of the single rivets. It appears, when plates are

riveted in this manner, that the strength of the joints is to the strength of the plates of equal sections of metal as the numbers,—

1000 : 1021 and 791*.

In a former analysis it was 1000 : 933 and 731,

which gives us a mean of 1000 : 977 and 761,

which in practice we may safely assume as the correct value of each. Exclusive of this difference, we must however deduct 30 per cent. for the loss of metal actually punched out for the reception of the rivets, and the absolute strength of the plates will then be, to that of the riveted joints, as the numbers 100, 68 and 46. In some cases, where the rivets are wider apart, the loss sustained is however not so great; but in boilers and similar vessels, where the rivets require to be close to each other, the edges of the plates are weakened to that extent. In this estimate we must however take into consideration the circumstances under which the results were obtained, as only two or three rivets came within the reach of experiment: and again, looking at the increase of strength which might be gained by having a greater number of rivets in combination, and the adhesion of the two surfaces of the plates in contact, which in the compressed rivets by machine is considerable, we may fairly assume the following relative strengths as the value of plates with their riveted joints:—

Taking the strength of the plate at	100
The strength of the double-riveted joint would then be . .	70
And the strength of the single-riveted joint	56

These proportions may therefore in practice be safely taken as nearly the standard value of joints, such as used in vessels where they are required to be steam- or water-tight, and subjected to pressure varying from 10 to 100 lbs. upon the square inch.

Since the above was written, I have ascertained, on a recent visit to Bristol, that the large steam-ship† now building there is double-riveted, the plates being three-fourths of an inch thick over the bottom and bilge, and five-eighths thick up to the water-line. These plates are

* The cause of the increase of strength in the double-riveted plates may be attributed to the riveted specimens being made from the best iron, whereas the mean strength of the plates is taken from all the irons experimented upon, some of inferior quality, which will account for the high value of the double-riveted joint. In ordinary cases and in practice it will therefore be safer to take the mean of the whole, viz.—

Strength of plates	100
Strength of double-riveting	97
And of single-riveting................	76

† The Great Britain steam-ship.

joined together with double rivets of 1 inch diameter, and inserted at distances of 3 inches apart. The proportions appear to be good; and conceiving the workmanship to be equally so, I should infer that this fine vessel would fairly establish the principle, that iron, in all the ramifications of ship-building, is an article of paramount importance to the war as well as to the mercantile navy.

In the pursuit of the foregoing inquiry, I was naturally led to the consideration of the best proportions and best forms of riveting plates together. I investigated this subject with great care, and from my own personal knowledge and that of others, I have collected a number of practical facts, such as long experience alone could furnish. From these data I have been enabled to complete the following Table, which for practical use I have found highly valuable in proportioning the distances and strength of rivets in joints requiring to be steam- or water-tight.

Table exhibiting the strongest forms and best proportions of riveted joints as deduced from the experiments and actual practice.

Thickness of plates in inches.	Diameter of rivets in inches.		Length of rivets from the head in inches.		Distance of rivets from centre to centre in inches.		Quantity of lap in single joints in inches.		Quantity of lap in double-riveted joints in inches.
·19 = $\frac{3}{16}$	·38		·88		1·25	6	1·25		
·25 = $\frac{4}{16}$	·50	2	1·13		1·50		1·50	6	
·31 = $\frac{5}{16}$	·63		1·38		1·63		1·88		For the double-riveted joint, add two-thirds of the depth of the single lap.
·38 = $\frac{6}{16}$	·75		1·63	4·5	1·75	5	2·00	5·5	
·50 = $\frac{8}{16}$	·81		2·25		2·00		2·25		
·63 = $\frac{10}{16}$	·94	1·5	2·75		2·50	4	2·75	4·5	
·75 = $\frac{12}{16}$	1·13		3·25		3·00		3·25		

The figures 2, 1·5, 4·5, 6, 5, &c. in the preceding Table are multipliers for the diameter, length and distance of rivets, also for the quantity of lap allowed for the single and double joints. These multipliers may be considered as proportionals of the thicknesses of the plates to the diameter, length, distance of rivets, &c. For example, suppose we take three-eighth plates and required the proportionate parts of the strongest form of joint, it will be—

$·375 \times 2 = ·750$ diameter of rivet, $\frac{3}{4}$ inch.
$·375 \times 4\frac{1}{2} = 1·688$ length of rivet, $1\frac{3}{4}$ inch.
$·375 \times 5 = 1·875$ distance between rivets, $1\frac{7}{8}$ inch.
$·375 \times 5\frac{1}{2} = 2·063$ quantity of lap, 2 inches.
$·375 \times 5\frac{1}{2} = 3·438$ quantity of lap for double joints, $3\frac{1}{2}$ inches.

·75, 1·68, 1·87, 2·06 and 3·43 are therefore the proportionate quantities necessary to form the strongest steam- or water-tight joints on plates three-eighths of an inch thick.

In the preceding pages I have endeavoured to investigate almost every circumstance having a practical bearing on the question of the strength of rolled plates, and the best methods of uniting them together. In conclusion, I would venture a few remarks on the value and judicious use of this material, in its adaptation to ship-building, and other purposes to which it may be successfully applied. It is not my intention to enter into the question as to whether wood or iron be the preferable material, as a number of circumstances, such as cost, durability, &c., must be considered in order to form a correct decision.

I would however observe, that in ship-building alone, it appears from the facts already recorded, that iron is very superior in its powers of resistance to strain; it is highly ductile in its character, and easily moulded into any required form without impairing its strength. It is also stronger in combination than timber, arising from the nature of the construction, and the materials composing the iron ship become a homogeneous mass when united together, forming as it were a solid, without joints, and presenting as a whole the most formidable powers of resistance*. These are some of the properties which appear to distinguish iron from other materials, and which give it an ascendency of combined action, which cannot be obtained in the union of timber however ingeniously contrived. It moreover possesses the property of lightness along with strength; in fact, its buoyancy, strength and durability constitute the elements of its utility in the innumerable cases to which it may be applied. In ship-building it possesses other advantages over timber. Its hull is free from the risk of fire; and in case of shipwreck, either on rocks or sand-banks, it will resist the heaviest sea, endure the severest concussion, and with proper attention to the construction, it may be the means of saving the lives of all on board. It moreover has the advantage of bulkheads, which, made perfectly water-tight, not only strengthen the vessel, but give greater security to it, and by a judicious arrangement in the divisions will float the ship under the adverse circumstance of a leak occurring in any one of the compartments. These are the qualities and powers of the iron ship; and I trust the present research into the strength and proportions of the material of which it is composed, will not only give increased confidence in its security, but will lead to

* Since the above was written we have had many examples of the enormous strength of iron ships, and amongst others we may instance an iron vessel which took the ground with nearly one-half of her length at the stern hanging over a shelf for a whole tide; another, the Vanguard iron steamer, which for several hours (under the action of a heavy surf) was beating upon sharp shelving rocks without going to pieces; and lastly, the Great Britain steam-ship, which was stranded in Dundrum Bay, and resisted the force of the winter storms for many months.

an extension of its application in every branch of marine and mechanical architecture.

PART III.

Resistance of Wrought-iron Plates to Pressure by a Blunt Instrument at right angles to the surface of the Plate.

Irrespective of the experiments made to determine the strength of wrought-iron plates and the relative strength of the joints by which they are united, the investigation would be incomplete if we omitted another inquiry of equal importance, namely, the resistance offered by plates to a crushing force, such as exhibited in the injuries received by vessels when stranded on rocks or taking the ground in harbours where the surfaces are uneven.

Almost every person connected with nautical affairs is acquainted with the nature of the injuries received by timber-built vessels when placed in circumstances affecting their stability, or when resting on hard and unequal ground, such as frequently occurs in tidal harbours at low water. Such a position is attended with danger under every circumstance; and in order to determine the relative values of the two materials, wood and iron, it was considered desirable to institute a similar class of experiments on both, and thus to afford the means of comparison between them. English oak, as the strongest and best material used for the construction of first class vessels, was selected for this purpose, and the results obtained from both are given, under circumstances as nearly similar as the nature of the experiment would admit. They are as follows.

In each of the experiments the plate was fastened upon a frame of cast iron, 1 foot square inside and 1 foot 6 inches outside, its breadth being 3 inches and thickness half an inch. The sides of the plates, when hot, were twisted round the frame, to which they were firmly bolted. The contraction, by cooling, caused it to be very tight, and the force to burst it was applied in the centre. This was done in order that the force might in some degree resemble that from a stone or other body with a blunt end pressing against the side or bottom of a vessel: a bolt of iron, terminating in a hemisphere 3 inches in diameter, had thus its rounded end pressed perpendicularly to the plate in the middle. The results are given in the following Tables.

TABLE XIII. Experiments to determine the Resistance of Plates of Wrought Iron to a force tending to burst them.

No. of exp.	Description of plates.	Weight laid on in lbs.	Permanent indentation of plate.	Remarks.
			inch.	
1.	Plate of the best Staffordshire iron ¼ inch thick.	8,617	·3	Plate not cracked.
		9,893	·35	Plate not cracked.
		11,169	·5	Crack on convex side 8 inches long.
		12,445	·6	Crack on convex side 9 inches long; not opened on concave side.
		13,789	·7	Hole through the plate about 1¼ inch long, and ⅛ inch wide.
2.	Plate of the same iron and the same thickness.	9,893	·25	Double crack on convex side 1 inch long.
		11,169	·34	Double crack increased.
		12,445	·4	
		13,789	·47	
		16,477	·6	Form of crack on convex side (⅛ inch wide).
		17,821	·65	Not cracked through.
		19,769	......	Cracked through.
3.	Plate of the same iron ½ inch thick.	18,523	......	No crack.
		21,075	·33	Incipient crack on convex side.
		22,787	·45	Crack above-mentioned 4 inches long, forming a cross.
		25,923	·60	Crack above, 6 inches long.
		29,059	·75	Crack above, ⅛ inch wide.
		32,195	·80	
		35,331	·97	
		36,899	1·10	No crack on concave side.
		37,519	......	Plate cracked through.
4.	Plate same as the last.	21,219	......	No crack.
		21,985	·35	Slight crack on convex side.
		27,708	·47	Form of crack on convex side.
		31,796	·7	Form of crack increased.
		33,431	·75	
		35,066	·83	Form of crack 4 inches deep.
		36,701	·97	Not cracked through.
		37,928	......	Cracked through.

In Plate V. figs. 13 and 14, will be found representations of the fractures of the plates experimented upon in this Table.

From the above we obtain the strength of plates to resist rupture from pressure from a blunt body, or a ball 3 inches diameter.

	lbs.	Mean.
In experiment 1, a plate one-fourth of an inch thick was burst by	13,789	16,779
In experiment 2, a plate one-fourth of an inch thick was burst by	19,769	
In experiment 3, a plate half an inch thick was burst by	37,519	37,723
In experiment 4, a plate half an inch thick was burst by	37,928	

Here the strengths are as the depths, a half-inch plate requiring double the weight to produce fracture that had previously burst the quarter of an inch plate. In the succeeding experiments on oak timber, the powers of resistance follow the ratio of the squares of the depth, so that a wrought-iron plate of only one-quarter of an inch thick is able to resist a force equal to that required in the rupture of a 3-inch plank.

The experiments were made upon good English oak, of different thicknesses, and of the same width as the iron plates. The specimens were laid upon solid planks, 12 inches asunder, and by the same apparatus the rounded end of the 3-inch pin was forced through them as follows:—

Resistance of planks of timber to the entrance of a ball, 3 inches diameter, the planks being laid upon props 12 inches asunder; the object of the experiments being to burst them by pressing a pin, terminated by a hemispherical end, 3 inches diameter, through the centre of the plank, as was done with the plates of iron.

TABLE XIV.

No. of exp.	Description of plank.	Weight laid on.	Remarks.
		lbs.	
1.	English oak, very dry and good, 11¼ inches broad, and 2¼ inches deep.	16,115 17,235	Indentation from hemisphere ¼ inch deep; wood otherwise uninjured. Hole through the middle, 3 inches diameter nearly broke out, all the rest remaining sound.
2.	English oak, rather green, 8 inches broad, 3 inches deep.	18,941	It bore 18,941 lbs. about ten minutes, and then exploded with violence, dividing into three parts, the middle one on which the pin rested being about an inch thick at the top, and ½ an inch at the bottom. With a ton less weight there was a crack under the plank in the centre, and an indentation by the pin ¼ inch deep on the upper side. Sap was driven out from the ends on the side nearest to the heart.
3.	English oak plank, and dimensions same as in last experiment.	12,445 16,925	Sap driven out as in last experiment; plank without crack; indentation by the pressure about ¼ inch. The plank split with bearing the pressure about ten minutes.
4.	English oak from same plank as in experiment 2 and 3; breadth 8 inches, depth 1½ inch.	4,532	The plank broke by splitting.
5.	English oak from same plank and same size as in the last experiment.	4,280	Broke by splitting diagonally.

Taking the results of the four last experiments, which were on pieces from the same plank, we obtain—

	lbs.	Mean.
Strength from planks 3 inches thick	18,941	17,933
Strength from planks 3 inches thick	16,925	
Strength from planks $1\frac{1}{2}$ inch thick	4,532	4,406
Strength from planks $1\frac{1}{2}$ inch thick	4,280	

Here the strength to resist crushing follows the ratio of the square of the depth, as is found to be the case in the transverse fracture of rectangular bodies of constant breadth and span.

If we compare the foregoing results with the experiments performed by Mr. Hodgkinson on timber, it will be found that the strength of dry English oak to resist a crushing force is 4·24 tons to the square inch, whereas wrought iron, according to Rondelet, requires a pressure of about 31 tons per square inch, and with this weight it is reduced about one-sixteenth of its length. The resistance of wrought iron to a crushing force is therefore about seven and a quarter times greater than that of oak: and according to the experiments in the preceding Table, it appears that the resistance of wrought-iron plates to a force calculated to burst them, follows a different law to that of oak, the resistance of the former being directly as the depth and of the latter as the square of the depth. Reasoning from these facts, it may be interesting to know that in the use of timber, such as the oak sheathing of ships, the strength to external pressure increases in the ratio of the squares of its thickness; and, where great strength is required, it will be necessary, in the construction of vessels, to consider the nature of the service and the required thickness of the planks.

The same remarks will apply to vessels constructed of iron, computed from the formula deduced from the experiments. In a table of experimental results by Mr. Hodgkinson we have the mean force per square inch required for crushing timber of different kinds; and assuming Rondelet's experiments, which give 70,000 lbs. as the resistance per square inch of wrought iron, to be correct, we then have as the ratio of their respective powers of resistance as follows:—

TABLE XV.

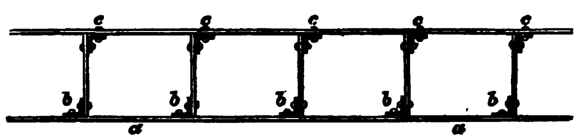
Specific gravities.	Description of timber used.	Resistance per square inch.	Resistance of wrought iron per square inch.	Ratio, the wood representing unity.
		lbs.	lbs.	
7·700	Wrought iron	......	70,000	
0·560	Yellow pine	5375	70,000	1 : 13·02
0·540	Cedar	5674	70,000	1 : 12·33
0·580	Red deal	5748	70,000	1 : 12·16
0·640	Birch	6402	70,000	1 : 10·93
0·660	Sycamore	7082	70,000	1 : 9·88
0·753	Spanish mahogany ...	8198	70,000	1 : 8·53
0·780	Ash	8683	70,000	1 : 8·06
0·700	Dry English oak	9509	70,000	1 : 7·36
0·980	Box	9771	70,000	1 : 7·16

In addition to the relative resisting forces of the different kinds of timber above enumerated, will be found the specific gravities of each, which enables the reader to determine the comparative weights as well as strength of the different kinds of wood.

PART IV.

In the preceding researches I have endeavoured to determine the value of iron chiefly in reference to its application for the purposes of ship-building. It now only remains to determine the best form and condition of another part of the structure, namely, the frames and ribs of vessels, also composed of iron. Some of the forms experimented upon indicate weakness, but certain modifications which have since been introduced have given increased support to the bilge and sides of the ship, and greater powers of resistance to the outer sheathing. The beam shown at fig. 19, Plate V., is probably one of the strongest and most suitable for the support of the decks, but it is inadmissible as a frame for receiving the exterior sheathing plates. These frames are generally formed of a plate with angle-irons along the edges on both sides, of which the annexed sketch are sections. *a*, *a*, &c. represents a

Fig. 15.

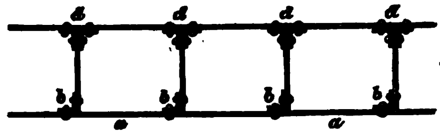


portion of the outside plates; *b*, *b* the angle-iron frames or ribs, which vary from 18 to 24 inches asunder, according to the position in the direction of the length of the ship; *c*, *c*, angle-iron of the same strength is riveted along the edge of each rib for the purpose of stiffening the sides of the ship and giving increased resistance to those parts, also to

receive interior plates, some of which, in large vessels, are riveted diagonally to the interior angle-irons *c, c,* &c., forming stringers and braces from the kelsons round the bilge to the upper decks.

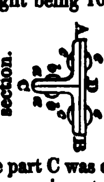
Other kinds of frames might be used with double angle-iron, as shown at *d, d,* &c. in the annexed sketch, but they are more expensive, and

Fig. 16.



from the increased complexity of construction, the extra strength obtained does not compensate for the difference of cost. Altogether, the frames recorded in fig. 15 have come into general use as the most effective and easy of construction. Those experimented upon were of different kinds, as shown in Plate V. figs. 17, 18, &c., and in sections given in the Tables, and from which the following results were obtained:—

Table XVI. Experiments to ascertain the strengths of uniform wrought-iron beams of different forms to support the sides and other parts of vessels, the beams having their ends placed upon props and being loaded in the middle.

No. of exp.	Description and form of the beam.	Weight laid on middle.	Deflections with these weights.	Breaking weight of the beam of 7 feet between the supports.	Weight of the beam of 7 feet 6 inches long.	Oak beams. Side of square of oak beams of equal strength with the iron one.	Oak beams. Weight of such beams of 7 feet 6 inches long and specific gravity 900.
		lbs.		lbs.	lbs.	inches.	lbs.
1.	Beam formed from two 2½ angle-irons, riveted together with rivets 6 inches asunder, and a plate a ½ inch thick riveted to the back, with rivets 4 inches asunder. Distance between the supports 7 feet, and whole length 7 feet 6 inches, its weight being 109 lbs.  Dimensions of section. Thickness. AB = 5 inches. CD = 2·6 inches. *aa* = ·5 inch. *bb* = ·56 inch. *cc* = ·64 inch. *ee* = ·25 inch. The part C was downwards during the experiment, the weight being laid upon the part D.			3355	109	3·6324	38 65

Remarks.—The weight 3355 lbs. was laid on at once, and the beam almost immediately sunk with it; a weight something less would have done it.

TABLE XVI. (continued).

No. of exp.	Description and form of the beam.	Weight laid on middle.	Deflections with these weights.	Breaking weight of the beam of 7 feet between the supports.	Weight of the beam of 7 feet 6 inches long.	Oak beams. Side of square of oak beams of equal strength with the iron one.	Oak beams. Weight of such beams of 7 feet 6 inches long and specific gravity 900.
		lbs.		lbs.	lbs.	inches.	lbs.
2.	The beam last used, cut in two; distance between supports 2 feet 3 inches; vertical rib downwards, that it might be stretched as before; weight of 3 feet 9 inches =54 lbs.	4,039	·18				
		5,383	·30				
		6,055	·43				
		6,727	·64				
		7,399	·88				
		7,735 sunk	...	2486	109	3·287	31·80
	Remarks.—With 7735 lbs. it sunk, by stretching and tearing at a rivet-hole.						
3.	The other half of the beam (exp. 1.), cut in two. Distance between the supports 2 feet 3 inches; weight of 3 feet 9 inches =55 lbs.; vertical rib upwards thus, ⊥ that fracture might take place by the compression of that rib.	4,039	·17				
		5,383	·23				
		6,055	·26				
		6,727	·34				
		7,399	·47				
		8,071	·63				
		8,743	·85				
		9,415	1·10				
		10,087	1·95				
		10,423	2·90				
		10,759 sunk	...	3458	109	3·6692	39·44
	Remarks.—With 10,759 lbs. it sunk; the vertical rib becoming twisted.						

All the beams experimented upon in the foregoing Table are shown in view and in section, Plate V. figs. 17 and 18. In the first experiment the beam was 7 feet between the supports, but having yielded to the first weight, 3355 lbs., laid on, it was subsequently cut in two, as shown in the drawings above referred to. In experiment 2, it will be observed that a frame of this form is weak, arising from the deficiency of material on the lower side of the rib formed by angle-iron, which, yielding to a tensile strain, becomes elongated in the act of bending, and would thus deflect through a considerable space before actual fracture took place. Reversing the other part of the beam with the broad flange downwards it carried more weight, but ultimately sunk under a load of 10,759 lbs., being in the ratio of 10 : 7 in favour of the beam with the rib upwards.

These experiments, when reduced to 7 feet between the supports, gave nearly the same proportion, viz. nearly as 34 : 24. They are however all weak, arising almost exclusively from want of material on the top edge of the ribs, and a due proportion in the construction of the beam.

TABLE XVII. Experiments on Wrought-iron Beams (continued).

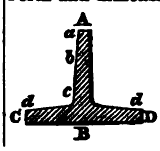
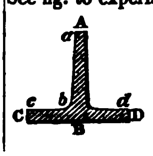
No. of exp.	Description and form of the beam.	Weight laid on middle.	Deflections with these weights.	Breaking weight of the beam of 7 feet between the supports.	Weight of the beam of 7 feet 6 inches long.	Oak beams. Side of square of oak beams of equal strength with the iron one.	Oak beams. Weight of such beams of 7 feet 6 inches long and specific gravity 900.
		lbs.		lbs.	lbs.	inches.	lbs.
4.	Beam differing from that in exp. 1 only in being of greater strength, this beam being formed of two 3-inch angle-irons, riveted as before to a plate a ¼-inch thick. Distance between the supports 7 feet; weight of the beam 7 feet 6 inches long, 167½ lbs.; vertical rib downwards ┬.	3,355 4,711 5,383 5,719 6,055 6,391 6,727 ...... 7,063 7,399	·40 ·62 ·82 ·98 1·12 1·30 1·87 1·92 2·29 3·25	7399	167·5	4·7281	65·49

Remarks.—After bearing the weight 7399 lbs. a short time the beam became cracked at a rivet-hole and sunk. From the experiments of Buffon upon green oak, the side of a square beam of equal strength would be 4·558 inches, and its weight 708 lbs.

No. of exp.	Description and form of the beam.	Weight laid on middle.	Deflections with these weights.	Breaking weight	Weight of the beam	Side of square of oak	Weight of oak beams
5.	Half the beam used in exp. 4, now 3 feet 9 inches long, and weighing 82½ lbs. Distance between supports 3 feet 6 inches; vertical rib downwards.	4,039 7,399 10,759 11,431 12,103 12,439	0·85 0·25 0·43 0·53 0·65 broke at a rivet-hole.	6219	1675	4·462	
6.	The other half of the beam in exp. 4, weighing 85 lbs.; length 3 feet 6 inches. Distance between the supports 2 feet 3 inches; rib upwards ┴.	8,304 12,392 16,480 18,115	0·12 0·24 0·75 sunk, the vertical rib being twisted.	5823	1675	4·3653	55·83

The whole of the experiments herein recorded are of the same description as the last, with the exception of the beam being composed of thicker angle-iron, and consequently rendered much stiffer and stronger than those first experimented upon. This increased stiffness reversed the resisting powers of the beam, when taken at a 7-feet span, in the ratio of 6 : 5 in favour of the first position with the rib downwards. For plans and sections of these beams see Plate V. fig. 18.

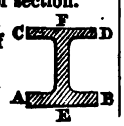
TABLE XVIII. Experiments on Wrought-iron Beams (continued).

No. of exp.	Description and form of the beam.	Weight laid on middle.	Deflections with these weights.	Breaking weight of the beam of 7 feet between the supports.	Weight of the beam of 7 feet 6 inches long.	Oak beams. Side of square of oak beams of equal strength with the iron one.	Oak beams. Weight of such beams of 7 feet 6 inches long and specific gravity 900.
		lbs.		lbs.	lbs.	inches.	lbs.
7.	Solid wrought-iron beam, 4 feet 2 inches long, weighing 23 lbs., placed upon props 4 feet asunder; vertical rib upwards. Form and dimension of section  Thickness at a = ·24 b = ·29 c = ·41 d = ·36 AB = 2·50 CD = 2·85	1394 1932 2470 2739 3008	·135 ·24 ·59 ·90 1·35	1790	41·4	2·9461	25·43
	Remarks.—With 3008 lbs. the elasticity was entirely destroyed, and a like additional weight would have destroyed the form of the beam.						
8.	Same beam rendered straight, and turned with its rib downwards T.	1394 1932 2470 2739 3008 3142	·17 ·25 ·66 1·22 2·20 sunk	1870	41·4	2·9894	26·18
9.	Solid beam, same form as before; length 5 feet $\frac{3}{8}$ inch; weight $25\frac{1}{4}$ lbs. Distance between supports 4 feet; rib upwards thus. See fig. to experiment 7.  Thickness at a = ·23 b = ·30 c = ·40 d = ·33 AB = 2·05 CD = 2·95	1394 1932 1526 2201 2335 } in a few minutes	·30 ·86 1·19 1·59 2·04 2·13	1334	37·6	2·671	20·90
	Remarks.—After bearing the weight, 2335 lbs., it had taken a permanent set, or flexure = 1·71 inch, and would have sunk more if it had not been unloaded.						
10.	Same beam rendered straight and turned upside down thus T. Distance between supports 4 feet.	1394 1932 2201 2335 } in a minute. 2469	·27 ·51 1·01 1·57 1·60 2·50	1411	37·6	2·7215	21·70
	Remarks.—After bearing 2469 lbs. it was unloaded, as a little additional weight would have destroyed its form.						

The experiments in this Table were made on solid T iron, and indicate nearly the same proportions, as respects their strength, as the beams composed of a plate and double angle-iron riveted together. The whole of these beams appear to be defective in form, and are therefore not calculated to sustain a severe transverse strain. To attain the section of greatest strength, it is probable a different form would be required, as well as a different proportion of the parts, such as in the annexed figure with a double flange*.

TABLE XIX. Experiments on Wrought-iron Beams (continued).

No. of exp.	Description and form of the beam.	Weight laid on middle.	Deflections with these weights.	Breaking weight of the beam of 7 feet between the supports.	Weight of the beam of 7 feet 6 inches long.	Oak beams.	
						Side of square of oak beams of equal strength with the iron one.	Weight of such beams of 7 feet 6 inches long and specific gravity 900.
		lbs.		lbs.	lbs.	inches.	lbs
11.	Beam of wrought iron, formed of two bars (nearly equal), whose section is riveted together; length of the beam 4 feet 2 inches; its weight 44lbs. 5 oz. Distance between the supports 4 feet.	4,195	0·75				
		7,465	0·148				
		10,735	0·22				
		10,735 laid on again.	......	......	......	......	......
		14,005	0·24 broke.	8336	79·76	4·9199	70·91
	Dimensions of section. AB = 2·86 inches. Mean thickness of AB = ·33 inch. EF = 3·70 inches.						

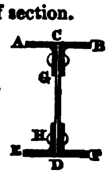


Remarks.—After bearing the weight 10,735 lbs., the beam had taken a set = ·06. Pieces of wood were driven tightly in between the ribs AB, CD, at each side of the beam in *the middle*, to prevent the load laid on it there from deranging its form. The beam broke by the bottom rib being torn asunder, preceded by one of the bars cracking at a rivet-hole.

The above is probably the strongest form of beam, if duly proportioned, by adapting the material to a balance of the two opposing forces of extension and compression.

* Since the experiments herein recorded were made, others have been instituted on some deck-beams by Mr. Kennedy of Messrs. Bury, Curtis and Kennedy, Liverpool, the particulars of which are inserted hereafter.

TABLE XX. Experiments on Wrought-iron Beams (continued).

No. of exp.	Description and form of the beam.	Weight laid on middle.	Deflections with these weights.	Breaking weight of the beam of 7 feet between the supports.	Weight of the beam of 7 feet 6 inches long.	Oak beams. Side of square of oak beams of equal strength with the iron one.	Oak beams. Weight of such beams of 7 feet 6 inches long and specific gravity 980.
		lbs.		lbs.	lbs.	inches.	lbs.
12.	Beam of wrought iron composed of a uniform vertical rib (7 inches deep and 7 feet 6 inches long) with two 2-inch angle-irons riveted to both top and bottom of the rib; rivets 4 inches asunder; weight of beam 161¼ lbs. Distance between the supports 7 feet. Dimensions of section. CD = 7 inches. AB = 4·5 inches. EF = 4·5 inches. Mean thickness of AB = ·28 in. EF = ·30 in. Plate GH = ·25. 	4,216 8,304 16,480 18,667 22,027 in five minutes. 24,379	·10 ·18 ·25 ·36 ·52 } ·54 sunk	24,379	161¼	7·0358	145·03
	Remarks.—With the weight 24,379 lbs. the top ribs of the beam became twisted.						
13.	Same beam rendered straight and uniform; experiment 12 repeated.	16,115 18,355 19,475 20,595 21,715	·29 ·36 ·42 ·51 sunk	21,715	161¼	6·7695	134·26
	Remarks.—The beam was heated by the smiths, and when reduced to its original form, it was allowed to cool gradually. With 21,715 lbs. it became bent, towards the wall, in a direction in which it was slightly drawn by the lever; ribs not twisted as before. It bore the weight a minute or two before giving way.						

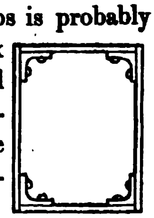
This experiment shows the superior quality of wrought-iron beams in giving timely notice before fracture; it further exhibits weakness on the top sides of the beams, a circumstance requiring great attention in their construction, which in some recent experiments, instituted for attaining the section of greatest strength, have been strikingly developed*.

In the preceding experiments, we have endeavoured to compare the strengths, as well as the weights of the beams or frames which form the ribs of ships. As regards the strengths with equal weights, it is in favour of oak; but the circumstance of the fastenings by rivets in the sheathing being so much superior to those of timber, the iron ship-

* See my work on the Construction of the Britannia and Conway Tubular Bridges.

builder is enabled to dispense with one-half the number of frames, and consequently a great reduction of weight is effected and more strength obtained in the vessel as a whole, than could possibly be accomplished in the timber-built ship, however ingenious the construction or the arrangement and distribution of the material. The very act of caulking the joints of a wooden vessel has a tendency to loosen the fastenings, whereas, in the iron ship, there are no actual joints, for the whole being bound together *en masse*, the same, or nearly the same, strength is obtained as if the whole ship were composed of solid plates and ribs.

The best sectional form of beams for the decks of ships is probably that exhibited in Table XX., which, along with the box beam of the annexed form for supporting the shafts and paddle-boxes of steamers, is that generally used in the construction of vessels of this description. Other forms have been adopted, particularly those suggested by Mr. Kennedy of Liverpool, alluded to in page xl. note.



Having carefully investigated the different properties of wrought iron in its varied forms of construction, and conceiving that the results obtained from the experiments may be useful in a variety of circumstances connected with the useful arts, I have endeavoured to collect them in the abstract, in order that the practical builder and engineer may the more readily ascertain the comparative value of the different forms of beams, the properties of the material, and their adaptation to any particular construction in which he may be engaged. Should further information be required, we must then refer to the experiments, in which will be found the facts more in detail, and which are probably better calculated to satisfy the inquiring mind and to effect that conviction essential to success.

I have not attempted any inquiry into the laws of oxidation, the adhesion of barnacles and marine vegetation, and the means necessary to prevent such evils. This is a subject which does not come within the province of the present inquiry, and more properly belongs to that of the chemist. I would however briefly notice, that in the whole of my experience I have had little to complain of from the effects of oxidation, as that destructive process, as regards iron, appears to be greatly mitigated, if not almost suspended, by constant use, and under the influence of vibratory action the operation appears to be rendered nugatory, if it does not entirely cease, and that under circumstances exceedingly difficult to explain. This is an investigation not unworthy the attention of some of our best chemists, to whom the causes may be known, but which are at present, as far as I know, unaccounted for. For example, I may mention that an iron ship, if kept constantly in use, or nearly so, will last

for a number of years exposed to all the changes of weather and temperature without any sensible appearance of decay. The same may be said of iron rails, over which are passing daily such enormous weights, and at such velocities as almost to neutralize the action of the elements. All these are striking examples of the durability of wrought iron, which may be considered as an important element of its security, and a recommendation for its extended application. There is another circumstance in connection with this subject to which it may be necessary in this place to advert, and that is the effect which a long continuance in salt water has upon the hull of an iron ship. It is well known that a long immersion of cast iron in the sea will convert it into plumbago, and that a similar process with malleable iron, from its contact with the saline particles of the ocean, produces oxidation; and in case the immersions were long continued, the effects of this destructive process might endanger the safety of the ship. As yet we have not had sufficient evidence of its effects to enable us to come to any definite conclusion, but it is not improbable that an occasional visit to harbours of fresh water may mitigate, if it does not entirely neutralize, the injurious effects which the material is likely to sustain. With these observations, which I offer with diffidence, I now beg to direct attention to the abstracts as deduced from the experiments.

Abstract of Results as obtained from the experiments.

In Part I. of this inquiry we have endeavoured to show that 50,000 lbs. per square inch is the mean breaking weight of iron plates, whether torn asunder in the direction of the fibre or across it; and we have also shown that the tensile strength of different kinds of timber drawn in the direction of the fibre varies in a given ratio to that of iron: the timber in this comparison being represented by unity, we have the following ratio of strength:—

	Timber :		Iron.
Ash as	1	:	2·94
Teak as..............	1	:	3·33
Fir as	1	:	4·16
Beech as	1	:	4·34
Oak as	1	:	5·00

These, for practical purposes, may be taken as a fair measure of the strength of the different woods as compared with that of iron plates.

It has been shown that wrought-iron plates, when riveted together, lose a considerable portion of their strength, as may be seen by the experiments in Part IV., where the plates, by their union with each

other, lose by the ordinary process of riveting 44 per cent., and by the best mode of riveting 30 per cent. This should not however create serious alarm, as the loss of strength is almost entirely obviated by the new process of riveting used in the bottom of the Britannia and Conway Tubular Bridges*; and it should also be observed that in timber the same injuries are sustained by splicing or any other method of forming the joints as are here exhibited in the riveting of iron plates. The two processes, that of riveting (according to the method used in the experiments) and splicing, when intended to resist a tensile strain, must therefore be considered analogous, and the comparison under such circumstances will nearly follow the same law as regards a diminution of strength.

In this section of the inquiry the results obtained from the experiments indicate a loss in the joints as compared with the solid plate, as the numbers 100, 70 and 56, viz.—

For the solid plate	100
For the double-riveted joint........	70
For the single-riveted joint	56

which numbers may be considered as a fair average value of the strengths of the different parts of vessels constructed in this manner.

Part V. exhibits the strength of plates to resist vertical pressure from a blunt instrument, which was forced through them for the purpose of ascertaining their comparative powers of resistance with oak timber, placed under circumstances precisely similar and subjected to the same force. The results are interesting, as the iron plates appear to follow a different law in their resistance to pressure to that of oak, the strength being as the depth or thickness of the plates in the first case, and as the squares of the depth in the second. The resistances are therefore in the ratio of 1 : 12, the iron being 12 times stronger than oak.

In Part IV. we have some curious facts illustrative of the necessity and value of experimental research. In the earlier experiments of the inquiry it is evident, that angle and T iron beams or frames are not the best, as regards form, to resist a transverse strain. In every case they are weak, and although exceedingly useful, and in fact indispensable for many purposes of construction, they are nevertheless not calculated to resist strain in the form of beams or girders. These defects I have endeavoured to obviate by the introduction of beams with double flanges formed of a body plate and riveted angle-irons at the top and bottom.

* See my process of chain-riveting as exhibited in the lower sides of the Britannia and Conway Tubular Bridges, where the injuries above enumerated are entirely obviated.

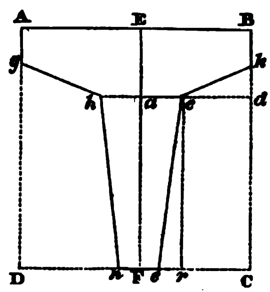
All these latter constructions may however be left with safety to the practical engineer*.

The strengths of nearly the whole of these beams have been mathematically investigated by Mr. Tate, to whose friendship and analytical research I am indebted for the annexed mathematical inquiry into the different forms of the wrought-iron beams which have been experimented upon. To the mathematician this part of the subject will be the more interesting, as the utmost care has been observed in the measurements and exact proportions of the parts, in order to obtain the necessary formula for calculating the strength of beams and frames of this description.

FORMULÆ RELATIVE TO THE BEAMS IN THE FOREGOING EXPERIMENTS.

Beams with a Single Flanch.

Let ABF be a section of a beam having a single flanch AB*kh*, the material being symmetrically distributed with respect to the vertical line EF. Let *hacd* and DFC be parallel to AB; *cr* and *kd*C parallel to EF. Put $EB = EA = e$, $CB = DA = e_1$, $ac = Fr = t$, $Bk = Ag = t_1$, $Ea = Bd = t_2$, $Fe = Fn = t_3$, area section AB*cenhg* $=$ A, and the distance of the centre of gravity of this section from the edge $ne = X$.



To find the Position of the Neutral Axis.

Assuming the material to be perfectly elastic, the neutral axis will be in the centre of gravity of the section. Hence we have, by calculating the moments with respect to the line DC,

$$A \times X = ee_1^2 - (e_1 - t_2)^2(e-t) - \frac{1}{3}(e_1 - t_2)^2(t - t_3) - (e-t)(t_2 - t_1)$$
$$\left(e_1 - \frac{2}{3}t_2 - \frac{1}{3}t_1\right),$$

$$\therefore X = \frac{3ee_1^2 - (e_1 - t_2)^2(3e - 2t - t_3) - (e-t)(t_2 - t_1)(3e_1 - 2t_2 - t_1)}{3A}, \quad (1.)$$

which expresses the distance of the neutral axis from the edge *ne*, where

$$A = (t + t_3)(e_1 - t_2) + (t_1 + t_2)(e - t) + 2tt_2 \quad . \; . \; . \; . \; . \; . \; . \quad (2.)$$

* For a more elaborate inquiry into the strengths of wrought-iron beams, see my work on the Britannia and Conway Bridges.

To find the Moments of Rupture.

Let I = the moment of inertia of the section about the neutral axis.

I_1 = the moment of inertia of the section about DC.

W = the breaking weight of the beam.

l = the distance between the supports.

S = the force per square inch of the material opposed to extension or compression, as the case may be, at the thin edge of the beam.

Taking DC as the axis,—

I_1 = moment inertia ABCD − 2 moment inertia *rCdc* − 2 moment inertia *erc* − 2 moment inertia *cdk*.

Now, moment inertia ABCD $=\frac{2}{3}ee_1^3$,

$$2 \text{ moment inertia } rCdc=\frac{2}{3}(e-t)(e_1-t_2)^3,$$

$$2 \text{ moment inertia } erc=\frac{1}{6}(t-t_3)(e_1-t_2)^3,$$

$$2 \text{ moment inertia } cdk=\frac{1}{6}(e-t)\{(e_1-t_1)^3-3(e_1-t_2)^3$$
$$+(e_1-t_1)(e_1-t_2)(2e_1-t_1-t_2)\}.$$

Substituting these values and reducing, we find

$$I_1=\frac{1}{6}[4ee_1^3-(e_1-t_2)^3(e-t_3)-(e-t)(e_1-t_1)\{(e_1-t_1)^2$$
$$+(e_1-t_2)(2e_1-t_1-t_2)\}] \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (3.)$$

Also (Moseley's Engineering, p. 82) we have

$$I=I_1-AX^2 \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (4.)$$

Moreover, by the formula of rupture,

$$\frac{Wl}{4}=\frac{SI}{X},$$

$$\therefore\ S=\frac{WlX}{4I} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (5.)$$

Taking the data of Table XVI., we have

$$e=2{\cdot}5,\ e_1=2{\cdot}6,\ t={\cdot}32,\ t_1={\cdot}35,\ t_3={\cdot}25,\ t_2={\cdot}42;$$

therefore, by equation (2.),

$$A=({\cdot}32+{\cdot}25)(2{\cdot}6-{\cdot}42)+({\cdot}35+{\cdot}42)(2{\cdot}5-{\cdot}32)+2\times{\cdot}32\times{\cdot}42=3{\cdot}19.$$

By equation (1.),

$$X=\{3\times 2{\cdot}5\times 2{\cdot}6^2-(2{\cdot}6-{\cdot}42)^2(7{\cdot}5-{\cdot}64-{\cdot}25)-(2{\cdot}5-{\cdot}32)\times({\cdot}42-{\cdot}35)(7{\cdot}8-{\cdot}84-{\cdot}35)\}\div 3\times 3{\cdot}19=1{\cdot}91,$$

which is the distance of the neutral axis from the edge *ne* of the beam.

By equation (3.),

$$I_1=\frac{1}{6}[4\times 2{\cdot}5\times 2{\cdot}6^3-(2{\cdot}6-{\cdot}42)^3(2{\cdot}5-{\cdot}25)-(2{\cdot}5-{\cdot}32)(2{\cdot}6-{\cdot}35)\times\{(2{\cdot}6-{\cdot}35)^2+(2{\cdot}6-{\cdot}42)(5{\cdot}2-{\cdot}35-{\cdot}42)\}]=13{\cdot}375.$$

By equation (4.),

$$I=13{\cdot}375-3{\cdot}19\times 1{\cdot}91^2=1{\cdot}738.$$

By equation (5.),

$$S=Wl\times\frac{1{\cdot}91}{4\times 1{\cdot}738}\text{ lbs.}=Wl\times\frac{1{\cdot}91}{15568}\text{ tons.}$$

In experiment 1, $W=3409$, $l=7\times 12=84$,

$$\therefore\ S=\frac{3409\times 84\times 1{\cdot}91}{15568}=35\text{ tons.}$$

Let X_1 = the distance of the neutral axis from the edges AB, and S_1 = the force per square inch opposed to extension or compression, as the case may be, at the edge AB, then

$$X_1=2{\cdot}6-1{\cdot}91={\cdot}69,$$

and $$S_1=\frac{X_1}{X}.S=\frac{{\cdot}69\times 35}{1{\cdot}91}=12{\cdot}6\text{ tons.}$$

In experiment 2, $W=7735+18=7753$, and $l=27$,

$$\therefore\ S=\frac{7753\times 27\times 1{\cdot}91}{15568}=25{\cdot}6\text{ tons.}$$

and $$S_1=\frac{{\cdot}69\times 25{\cdot}6}{1{\cdot}91}=9{\cdot}3\text{ tons.}$$

In experiment 3, $W=10759+18=10777$, $l=27$,

$$\therefore\ S=\frac{10777\times 27\times 1{\cdot}91}{15568}=35\text{ tons,}$$

and $$S_1=12{\cdot}6\text{ tons.}$$

Taking the data of Table XVIII., experiments 7 and 8,

$$e=1{\cdot}425,\ e_1=2{\cdot}5,\ t={\cdot}2,\ t_1={\cdot}36,\ t_2={\cdot}4,\ t_3={\cdot}12.$$

Hence we find from equation (2.), $A=1{\cdot}762$; from equation (1.),

$X=1{\cdot}86$, and $\therefore X_1=2{\cdot}5-1{\cdot}86={\cdot}64$; from equation (3.), $I_1=6{\cdot}943$; and from equations (4.) and (5.), $S=Wl\times{\cdot}00021$ tons.

In experiment 7, $W=3008+11=3019$, $l=48$,

$$\therefore S=3019\times48\times{\cdot}00021=30{\cdot}4 \text{ tons},$$

and $$S_1=\frac{{\cdot}64\times30{\cdot}4}{1{\cdot}86}=10{\cdot}4 \text{ tons}.$$

In experiment 8, $W=3142\times11=3153$, $l=48$,

$$\therefore S=3153\times48\times{\cdot}00021=31{\cdot}7 \text{ tons},$$

and $$S_1=\frac{{\cdot}64\times31{\cdot}7}{1{\cdot}86}=10{\cdot}9 \text{ tons}.$$

Observations.—The value of S determined from experiment 1, is the resistance of the material to extension, whereas the value of S determined from experiment 3, is the resistance to compression. Hence it appears, that in beams of this form and *thickness of plates* the resistance to extension is equal to that of compression. The same observation applies to the values of S determined from experiments 7 and 8; and the same law also holds true for experiments 9 and 10.

These calculations further show, that the material in these beams is not properly distributed, for while the thin side of the beam is about to undergo rupture, the broad side has not attained one-half of the tension or compression, as the case may be, which it is capable of sustaining.

It will also be observed, that the resistance of the material at the thin side, as indicated by these calculations, is greater than what it would be under ordinary circumstances, viz. about 25 tons per square inch. This apparent discrepancy may be explained as follows:—as a beam of wrought iron approaches the limit of tension it undergoes an accelerated rate of elongation, even while the cohesion of the material remains unimpaired*. Now this unusual extension of the particles in the lower laminæ (in a beam having a single flanch placed upwards) allows a succession of particles in the higher laminæ to come into full tensile strain, so that the particles at the lower edge of the beam apparently attain a tensile strain greater than they would have under ordinary circumstances. And it may be presumed, that a similar law obtains in reference to the compression of wrought-iron beams. Hence it follows, that all calculations which assume the tensile or compressive forces, in beams of this form, at the edges of the beam equal to what they are under ordinary circumstances, must lead to erroneous results.

It may be further worthy of remark, that experiments 2 and 3, 8 and 7, show that when the flanches of the beams are placed upwards the deflections are considerably greater than what they are when the flanches

* See remarks on experiment 2, p. liv.

are placed downwards; thus in experiments 2 and 3, we have

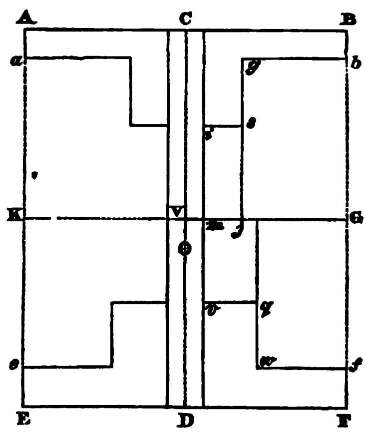
Weight on the beams. lbs.	Deflections when the flanch is upwards. inch.	Deflections when the flanch is downwards. inch.
6055	·43	·26
6727	·68	·34
7399	·88	·47

and in experiments 8 and 7,

2470	·66	·59
2739	1·22	·90
3008	2·20	1·35

Beams with a Double Flanch.

Let ABFE be a section of a beam having two flanches AB*ba* and EF*fe* formed by angle-irons riveted to a vertical plate CD, the material being symmetrically distributed with respect to the vertical line CD. Let O be the neutral axis, and KVG a line passing through the centre V of the vertical line CD parallel to AB or EF. Put A = the area of the section of the material, A_1 = area ABFE or 2 area ABGK, A_2 = 2 area *mjsi*, A_3 = 2 area *jgb*G, a_2 = 2 area *mjqv*, a_3 = 2 area *jwf*G, D_1 = GB = GF, D_2 = *sj*, D_3 = *b*G, d_2 = *jq*, d_3 = *f*G, X = OV, I_1 = moment of inertia about KG, I = moment of inertia about O, W = the breaking upon the centre of the beam, *l* = the distance of the supports, S, S_1 = the resistance of the material per square inch at the edges EF and AB respectively.



To find the Neutral Axis.

Taking KG as the axis of moments,

$$A \times X = \frac{1}{2}(A_2D_2 + A_3D_3 - a_2d_2 - a_3d_3),$$

$$\therefore \quad X = \frac{A_2D_2 + A_3D_3 - a_2d_2 - a_3d_3}{2A} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (6.)$$

where $\quad A = A_1 - A_2 - A_3 - a_2 - a_3. \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (7.)$

To find the Moments of Rupture, &c.

Taking the moments of inertia with respect to the line KG,

I_1 = moment inertia ABFE − 2 moment inertia space *bgsiqf*

$$=\frac{1}{3}(A_1D_1^2-A_2D_2^2-A_3D_3^2-a_2d_2^2-a_3d_3^2) \quad \text{(8.)},$$

$$I=I_1-AX^2 . \quad \text{(9.)}$$

$$S=\frac{Wl(D_1-X)}{4I} \quad \text{(10.)}$$

and

$$W=\frac{4SI}{l(D_1-X)} . \quad \text{(11.)}$$

If $a_2=A_2,\ a_3=A_3,$

then $X=0,\ I_1=I,$

and $I=\frac{1}{3}\left\{A_1D_1^2-2A_2D_2^2-2A_3D_3^2\right\},$

$$\therefore\ S=\frac{WlD_1}{4I}$$

$$=\frac{3WlD_1}{4\{A_1D_1^2-2A_2D_2^2-2A_3D_3^2\}} \quad \text{(12.)}$$

and

$$W=\frac{4S(A_1D_1^2-2A_2D_2^2-2A_3D_3^2)}{3lD_1}, \quad \text{(13.)}$$

which expresses the breaking weight when S is given.

Let D'_1, D'_2, ..., A', A_1, ... &c. be the corresponding dimensions of a beam in all respects similar, and let r be the ratio of the linear dimensions, then

$D'_1=rD'_1$, &c., $A'=r^2A_1$, &c., $A'_2D'_2=r^3A_2D_2$, &c., $A'_1D'^2_1=r^4A_1D_1^2$, &c.

By equation (6.),

$$X'=\frac{A'_2D'_2+A'_3D'_3-a'_2d'_2-a'_3d'_3}{2A'}$$

$$=\frac{r^3A_2D_2+r^3A_3D_3-r^3a_2d_2-r^3a_3d_3}{2r^2A}$$

$$=r\times\frac{A_2D_2-A_3D_3-a_2d_2-a_3d_3}{2A}$$

$$=r\times X.$$

By equation (8.),

$$I'_1=\frac{1}{3}\left\{A'_1D_1^2-A'_2D'^2_2-A'_3D'^2_3-a'_2d'^2_2-a'_3d'^2_3\right\}$$

$$=r^4\times\frac{1}{3}\left\{A_1D_1^2-A_2D_3^2-A_3D_3^2-a_2d_2^2-a_3d_3^2\right\}$$

$$=r^4\times I_1.$$

By equation (11.),

$$W' = \frac{4SI'}{l'(D_1' - X')}$$

$$= \frac{4S \times r^4 I}{rl(rD_1 - rX)}$$

$$= r^2 \times \frac{4SI}{l(D_1 - X)}$$

$$= r^2 \times W. \quad \ldots \quad (14.)$$

That is, THE BREAKING WEIGHTS IN SIMILAR BEAMS ARE TO EACH OTHER AS THE SQUARES OF THEIR LIKE LINEAR DIMENSIONS.

The method of demonstration here used in establishing this important theorem may be applied to any other form of beam.

When the sections of the beams are similar, but the distance between the supports any quantity l_1, then we have

$$W' = \frac{l'}{l_1} . r^2 W. \quad \ldots \quad (15.)$$

Suppose W in equation (11.) to be determined by experiment, then we are at liberty to assume

$$W = \frac{AdC}{l},$$

where d is the depth of the beam, and C a constant determined by the assumed relation.

From equation (14.), $W' = r^2 W$

$$= r^2 . \frac{AdC}{l}$$

$$= \frac{r^2 A . rd . C}{rl}$$

$$= \frac{A'd'C}{l'}. \quad \ldots \quad (16.)$$

That is, THE BREAKING WEIGHTS IN BEAMS ARE FOUND BY MULTIPLYING TOGETHER THE AREA OF THE SECTION, THE DEPTH, AND A CONSTANT DETERMINED FROM EXPERIMENT ON BEAMS OF THE PARTICULAR FORM, AND DIVIDING THIS PRODUCT BY THE DISTANCE BETWEEN THE SUPPORTS.

The value of l' in this formula is not restricted to the condition of similarity.

In experiment 12,

$D_1=3{\cdot}5,\ D_2=1{\cdot}375,\ D_3=3{\cdot}22,\ d_2=1{\cdot}375,\ d_3=3{\cdot}2,\ W=24380+80$
$=24460,\ l=84,$

$A_1=4{\cdot}5\times7=31{\cdot}5,\ \ A_2=1{\cdot}375\times{\cdot}28\times2={\cdot}7,\ \ A_3=3{\cdot}22\times1{\cdot}845\times2$
$=11{\cdot}8818,$

$a_2=1{\cdot}375\times{\cdot}3\times2={\cdot}75,\ \ a_3=3{\cdot}2\times1{\cdot}825\times2=11{\cdot}68,$

$A=A_1-A_2-A_3-a_2-a_3=32{\cdot}5-25{\cdot}01=6{\cdot}48,$

$\therefore$ by equation (6.), $X={\cdot}0611.$

By equation (8.), $I_1=46{\cdot}782.$

By equation (9.), $I=46{\cdot}782-6{\cdot}48\times{\cdot}0611^2=46{\cdot}758.$

By equation (10.),

$$S=\frac{24460\times84(3{\cdot}5-{\cdot}0611)}{4\times46{\cdot}758\times2240}=17 \text{ tons nearly,}$$

and $S_1=17\frac{1}{8}$ tons nearly.

In experiment 13, $W=21715+80=21800$ nearly,

and $$S_1=\frac{21800\times84(3{\cdot}5+{\cdot}0611)}{4\times46{\cdot}7854\times2240}=15{\cdot}5 \text{ tons,}$$

$$S=\frac{21800\times84(3{\cdot}5-{\cdot}0611)}{4\times46{\cdot}7854\times2240}=15 \text{ tons.}$$

The values of S and S_1, as determined by these calculations, being less for the beam in experiment 13 than they are for the beam in experiment 12, it follows that the latter has a better distribution of the material than the former. And at the same time the difference of the value of these constants is so small as to lead us to infer that the form of the beam in experiment 12 approaches to that of maximum strength with a given quantity of material. The sectional areas of the top and bottom flanches are to each other as 28 : 30 or 14 : 15, which is very nearly a ratio of equality.

APPENDIX.

Experiments by Thomas Loyd, Esq., Inspector of Machinery, to ascertain the effect of a tensile strain upon bars of wrought iron under varied conditions. Twenty pieces of $1\frac{5}{8}$ S C bar iron, each 10 feet long, were cut out of the middle of twenty rods of iron. These 10-feet lengths were cut into two parts of 5 feet each, and marked with the same letter. A, B, C, &c. were first broken so as to get the average breaking strain. A^2_2, B^2_2, C^2_2 were subjected to the constant action of three-fourths of the breaking weight for five minutes. The load was then taken off, and they were afterwards broken. It will be seen that the breaking

strain was about the same as before, thus proving that the previous strain had not weakened them.

Experiment 1.

First.				Second.			
Mark on the bars.	Dimensions of the bars.	Breaking weight in tons.	Ultimate elongation of bar in inches.	Mark on the bars.	Dimensions of the bars.	Breaking weight in tons.	Ultimate elongation of bars in inches with 25 tons.
A.	1·37	33·75	9·12	A 2.	......	33·75	1·56
B.	1·37	30·00	9·12	B 2.	......	33·00	1·61
C.	1·37	33·25	9·75	C 2.	......	33·25	1·56
D.	1·37	32·75	9·22	D 2.	......	32·25	1·75
E.	1·37	32·50	9·22	E 2.	......	32·50	1·75
F.	1·37	33·25	10·50	F 2.	......	33·00	1·56
G.	1·37	32·75	8·50	G 2.	......	33·00	1·61
H.	1·37	33·25	10·61	H 2.	......	33·50	1·50
I.	1·37	33·50	8·37	I 2.	......	32·75	1·67
J.	1·37	33·50	9·22	J 2.	......	33·25	1·67
K.	1·37	32·25	8·00	K 2.	......	32·50	1·86
L.	1·37	32·25	7·50	L 2.	......	31·50	2·00
M.	1·37	30·25	9·12	M 2.	......	32·75	Broke mark 1·75 in s. c.
N.	1·37	34·25	9·22	N 2.	......	34·00	1·12
O.	1·37	31·75	7·61	O 2.	......	32·50	1·75
P.	1·37	29·75	10·00	P 2.	......	31·00	1·75
Q.	1·37	33·50	9·22	Q 2.	......	33·75	1·50
R.	1·37	33·75	9·75	R 2.	......	33·75	1·56
S.	1·37	33·00	9·12	S 2.	......	33·25	1·12
T.	1·37	32·25	8·75	T 2.	......	31·00	2·18
Mean	......	32·87	9·09		......	32·81	1·64

In the first columns of the experiments it will be observed that the force required to break the bars was 32·37 tons, with a mean stretch of 9 inches upon twenty bars. In the second column the mean of the elongations, with a strain of 25 tons, was only 1·6 inch, whereas the ultimate breaking strain was 32·8 tons, evidently showing an increase instead of a diminution of strength from the previous strain of 25 tons, to which the bars had been respectively subjected.

Experiments made in the testing-machine of Woolwich Dockyard to ascertain the effect upon iron-bolt staves or iron bars to a tensile strain. The following results show the strains required for each of four successive breakages of the same pieces of iron as in the first experiment, $1\frac{3}{8}$ths of an inch diameter S C.

Experiment 2.

Distinguishing mark.	First breakage.		Second breakage.		Third breakage.		Fourth breakage.		Reduced from 1·37 to
	Tons.	Stretch in 54 inches.	Tons.	Stretch in 36 inches.	Tons.	Stretch in 24 inches.	Tons.	Stretch in 15 inches.	
		in.		in.		in.		in.	in.
A.	33·75	9·125	35·5	2·00					
C.	33·75	9·250	35·25	·25	37·00	1·00	38·75	......	1·25
E.	32·5	9·250	34·75	1·25					
F.	33·25	10·500	35·50	1·12	37·25	·62	·40	......	1·18
G.	32·75	8·500	35·00	1·25	37·5	......	·41	......	1·25
H.	33·75	10·625	36·25	1·87					
I.	33·50	8·375	34·50	·62	36·5	1·50			
J.	33·50	9·250	36·00	·25	36·75	1·120	41·75	......	1·25
L.	32·25	Defective	36·50	1·5	37·75	......	41·00	·31	1·25
M.	30·25	Defective	36·50	·62	37·75	·06	38·50	·06	1·25
Mean	32·92	......	35·57	......	37·21	......	40·16	......	1·24
Mean per square inch	23·94	......	25·86	......	27·06	......	29·20	......	·90

The results of the above experiments are highly interesting, as they not only confirm those previously made, but they indicate a progressive increase of strength, notwithstanding the reduced sectional area of the bars. These interesting facts are of considerable value, as they show that a severe tensile strain is not injurious to the bearing powers of wrought iron even when repeated to the extent of four times. In practice it may not be prudent to test bars and chains to their utmost limit of resistance; it is however satisfactory to know that in cases of emergency those limits may be approached without incurring serious risk of injury to the ultimate strength of the material.

It is further important to observe, that the elongations are not in proportion to the forces of extension; thus in the bar F, experiment 2, the elongation of a bar 54 inches long with 33·25 tons, is 10·5 inches, giving an elongation per unit of weight and length $=\frac{10{\cdot}5}{33{\cdot}25\times 54}=\cdot0058$; whereas an additional weight of 2·25 tons produces an elongation of 1·25 inch in 36 inches length of bar, giving an elongation per unit of weight and length $=\frac{1{\cdot}25}{2{\cdot}25\times 36}=\cdot0154$; that is, the elongation in this latter case is about three times that in the former.

Experiments made to ascertain whether a shorter bar of iron is stronger than a longer one of the same kind and size, $1\frac{5}{8}$ths of an inch diameter, S C.

Experiment 3.

Length between the nippers 10 feet.						
Distinguishing mark.	Stretch in 10 feet.	Breaking strain.	Mean.	Reduced at fracture.	To elsewhere.	Remarks.
	in.	tons.	tons.	in.	in.	
1.	26·00	33·00	32·21	1	1·25	Mean of elongation 26 inches.
2.	26·75	31·75		......	1·18	
3.	26·25	32·25		......	1·25	
4.	23·00	32·00		......	......	
5.	27·50	32·25		B.	B.	
6.	26·75	32·00		1·06	......	

Experiment 4.

Length between the nippers 42 inches.						
Distinguishing mark.	Stretch in 42 inches.	Breaking strain.	Mean.	Reduced at fracture.	To elsewhere.	Remarks.
	in.	tons.	tons.	in.	in.	
B.	9·50	32·50	32·125	1·06	1·25	Mean of elongation 9·8 inches.
B.	9·37	33·00		B.	......	
B.	10·25	31·75		1	B.	
B.	10·37	31·50		......	B.	
B.	8·62	32·00		1·06	F.	
B.	8·87	32·00		F.	F.	

Experiment 5.

Length between the nippers 36 inches.						
Distinguishing mark.	Stretch in 36 inches.	Breaking strain.	Mean.	Reduced at fracture.	To elsewhere.	Remarks.
	in.	tons.	tons.	in.	in.	
A.	8·50	32·25	32·25	1·06	1·25	Mean of elongation 8·8 inches.
A.	8·75	32·25		1	B.	
A.	9·00	31·25		F.	B.	
A.	9·12	31·50		......	......	
A.	9·37	33·50		B.	B.	
A.	8·87	33·25		B.	B.	

Experiment 6.

Length between the nippers 24 inches.						
Distinguishing mark.	Stretch in 2 feet.	Breaking strain.	Mean.	Reduced at fracture.	To elsewhere.	Remarks.
	in.	tons.	tons.	in.	in.	
C 1.	6·00	31·75	32·00	1	1·25	Mean of elongation 6·2 inches.
C 2.	6·62	31·50		1·06 B.	F.	
C 3.	6·12	32·50		1		
C 4.	6·12	31·75		1		
C.	6·00	32·25		1		
C.	6·37	32·25		......	B.	

Experiment 7.

Length between the nippers 10 inches.						
Distinguishing mark.	Stretch in 10 inches.	Breaking strain.	Mean.	Reduced at fracture.	To elsewhere.	Remarks.
	in.	tons.	tons.	in.	in.	
A.	4·00	32·25	32·29	1·06	1·25	Mean of elongation 4·2 inches.
A.	3·87	32·50				
A.	4·62	30·50		B.	B.	
A.	4·75	31·50		1	1·18	
A.	4·00	33·25		......	1·25	
A.	4·12	33·75				

Abstract of the foregoing.

Length between the nippers.	Breaking strain in tons.	Mean elongation in inches.
in.		
120	32·21	26
42	32·125	9·8
36	32·35	8·8
24	32·00	6·2
10	32·29	4·2

As these experiments were made upon the same description of iron, it may be fairly inferred that the length of a bar does not in any way affect its strength.

Reduction of the preceding Table.

Length of bar.	Elongation.	Elongation per unit of length.
in.		
120	26	·216
42	9·8	·233
36	8·8	·244
24	6·2	·258
10	4·2	·420

Here it appears that the rate of elongation of bars of wrought iron increases with the decrease of their length; thus while a bar of 120 inches has an elongation of ·216 inch per unit of its length, a bar of 10 inches has an elongation of ·42 inch per unit of its length, or nearly double what it is in the former case. The relation between the length of and its maximum elongation per unit, may be approximately expressed by the following formula, viz.—

$$l = \cdot 18 + \frac{2\cdot 5}{L},$$

where L represents the length of the bar, and l the elongation per unit of length of the bar.

These results are of some value, as they exhibit the ductility of wrought iron at a low temperature, and also the greatly increased strength which it exhibits with a reduced section under severe strain.

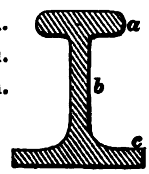
On some future occasion we may refer to this subject in order to show the bearing powers of wrought iron when compared with its elongated transverse section when reduced by forces sufficient to ensure fracture.

The following experiments were made to determine the transverse strength of beams, recommended by Mr. Kennedy of Liverpool, for supporting the decks of iron ships.

Experiment 8.—October 10, 1845.

On a malleable iron beam, of the annexed sectional form, 11 feet 7 inches long, and 11 feet between the supports.

Dimensions at a = 1·000 in. × 2$\frac{1}{2}$ in.
Dimensions at b = ·325 in. × 7 in.
Dimensions at c = ·380 in. × 4 in.
Weight of beam = 227 lbs.
Weight of shackle = 885 lbs.



Weight in lbs.	Deflection in inches.	Deflection load removed.	Remarks.
885	·04		
2,581	·12		
4,317	·20		
6,050	·26		
7,743	·35		
9,493	·46		
11,253	·60	·09	
12,955	......	......	With this weight the beam became distorted, and continuing the weight for some time, the deflection kept increasing until it bent laterally so as to be no longer able to sustain the load.
Ultimate deflection = ·69.			

Experiment 9.—October 10, 1845.

On a malleable iron beam, of the annexed sectional form (see fig. 66), 10 feet 8 inches long, and 10 feet between the supports.

Dimensions at a = 1·000 in. × 2$\frac{3}{7}$ in.
Dimensions at b = ·350 in. × 8 in.
Dimensions at c = ·440 in. × 4·30 in.
Weight of beam = 247 lbs.
Weight of shackle = 885 lbs.

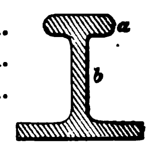
Weight in lbs.	Deflection in inches.	Deflection load removed.	Remarks.
885			
2,631	·04		
4,358	·12		
6,098	·15		
7,827	·19		
9,585	·21		
11,278	·26		
12,980	·30	·03	
14,693	·35	·03	
16,373	·45	·09	
18,115	·68	·26	
18,962	......	......	With this weight the beam was distorted and the experiment discontinued.
Ultimate deflection =·71.			

In both these experiments the beams yielded to lateral deflection, showing certain defects of form arising from want of lateral strength and breadth in the top and bottom flanges.

Experiment 10.—October 10, 1845.

Malleable iron beam of the same form as the last, 10 feet 7 inches long and 10 feet between the supports.

Thickness, $a = 1{\cdot}000$ in. $\times$ 2·75 in.
Thickness, $b = {\cdot}380$ in. $\times$ 8 in.
Thickness, $c = {\cdot}420$ in. $\times$ 4·30 in.
Weight of beam = 276 lbs.



Weight in lbs.	Deflection in inches.	Deflection load removed.	Remarks.
885	·020		
2,606	·050		
4,364	·090		
6,105	·100		
7,835	·140		
9,559	·165	·03	
11,257	·195	·03	
12,999	·220	·04	
14,728	·250		
16,407	·250		
18,108	·290		
19,839	·370		
21,553	·475	......	With 21,553 lbs. the deflection increased in four minutes ·025; in the next four minutes ·10; and in four minutes
22,387	·590		more it had sunk to ·34.
23,046	......	......	Bent laterally upwards of 2·65 inches, when the experiment was discontinued.
Ultimate deflection =·6.			

In these experiments it will be necessary to remark, that they were made with the narrow flange uppermost; a position rather favourable to the strength than otherwise, on account of the increased area of the top flange, which is equal to 2·75 inches; and the bottom flange is only 1·8 inch, a circumstance (deduced from subsequent experiments) favourable to the resisting powers of a wrought-iron beam.

Manchester, April 10, 1850.

APPENDIX II.

Experimental Researches to determine the Strength of Locomotive Boilers, and the Causes which lead to Explosion.

A difference of opinion having arisen between a gentleman high in authority and myself concerning the causes of an accident which took place through the explosion of a locomotive engine at Manchester, on the Eastern Division of the London and North-Western Railway, I deemed it necessary to institute a series of experiments, not for the purpose of confuting the arguments of others or confirming my own, but to determine the real causes of the explosion, and to register the observed facts for our future guidance in guarding against such fearful catastrophes.

After a careful examination of the boiler a few hours subsequent to the explosion, I found one side of the fire-box completely severed from the body of the boiler, the interior copper box forced inwards upon the furnace; and with the exception of the cylindrical shell which covers the tubes, the whole of the engine was a complete wreck, as exhibited in the annexed plate.

Mr. Ramsbottom, the Locomotive Superintendent, in his Report to the Directors, states that "the engine in question was made by Messrs. Sharp, Roberts and Co. in the year 1840, has been worked at a pressure of 60 lbs. per square inch, and has run in all a distance of 104,723 miles, a great part of which has been either entirely without load, or nearly so. As the cylinders are only 13 inch diameter, it has been for some time too light to work any of our trains; and has therefore been chiefly employed since 1849 in piloting the trains through Standedge tunnel, along with another engine of the same size, which is now at work.

"The fire-box was originally $\frac{7}{16}$ths of an inch thick, and is now a little over $\frac{6}{16}$ths of an inch; and from its excellent condition, might well be supposed (as indeed it was by Mr. Sharp, of the firm of Sharp Brothers and Co., who inspected it a few days after the accident) to have been recently put in new. It is perfectly free from flaw or patch, and would certainly have run at least 100,000 miles. The same may also be said with respect to the outer shell, which is nearly of the original thickness. The engine had been in the repairing shop the three months previous to the accident; and the iron fire-box stays, about which so much has been said, were tested by the hammer in the usual way, and were considered, both by the workmen and the foreman, Wheatley, to be all sound. When originally made, they were $\frac{11}{16}$ths in diameter, and were equal to a strain of at least ten times the force they had to sustain. With the exception of one stay, which was on the top row, the one most reduced from oxidation was half-inch diameter; and supposing the hold on the copper box to have been good, it was capable of resisting a strain of rather more than $6\frac{1}{2}$ times the working pressure, equal, say, to 390 lbs. per square inch. The only point therefore which could admit of doubt as to the safety of the boiler, was with respect to the hold which the stays might have in the copper box; but it appears, from experiments which I have since made, and which are about to be repeated by Mr. Fairbairn, that from the force required to pull some of the old stays out of a copper plate similar to the fire-box, into which they had been screwed by the *old threads only*, and *not riveted*, the boiler could not have burst under a pressure of less than 300 lbs. per square inch. One of the old stays, which had had the thread partially damaged from being ripped out of the copper box by the explosion, was screwed by hand into a copper plate, by the old thread, to a depth equal to the thickness of the fire-box plate, but not riveted, and it required a dead weight of 8204 lbs. to pull it out; and as each stay has to support a surface of 5 inches, $\times 5\frac{3}{8}$ inches, say 27 square inches only, it follows that a pressure of $8204 \div 27 = 303{\cdot}85$ lbs. per square inch would have been required to strip it.

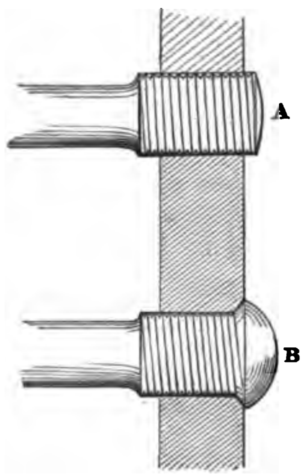
"Another stay, which had not been stripped by the explosion, but which was screwed out of the old box, was similarly treated, and required a force of 9·184 lbs. to strip it, equal to 340 lbs per square inch."

Since the experiments here referred to were made, I have repeated them with great care; and taking into account the tensile strength of the stays—in their corroded state—of the side of the fire-box, which to appearance was the first to give way, I find that a force of 380 lbs. upon the square inch would be required to effect rupture; and the results of

the experiments on the resistance of stays screwed into the copper fire-box fully confirm those already made by Mr. Ramsbottom. Assuming therefore that the ends of the screws were riveted, and sound in other respects, we may reasonably conclude that a strain of not less than 450 to 500 lbs. upon the square inch would be required to strip the screws, or tear the stays themselves asunder. I have founded these facts upon the experiment of the resisting powers of the iron stay screwed into a portion of the copper cut out of the ruptured fire-box, and another experiment of a similar stay first and then riveted, as shown in the annexed sketch.

The stay marked A, $\frac{3}{4}$ths of an inch in diameter, in the first experiment required a force of 18,260 lbs. = 8·1 tons to strip the screw, and draw it out of the copper; and the stay B, of exactly the same dimensions, but riveted over the end, required a force of 24,140 lbs. = 10·7 tons before it was dislodged*. Taking therefore the mean of those experiments, including those of Mr. Ramsbottom, and we arrive at the results given above, namely, a resisting power of 785 lbs. on the square inch, to burst or produce fracture in the stays and side of the fire-box.

Fig. 2.



In locomotive engines of more recent construction, where the stays are thicker and formed into squares of 4 to $4\frac{1}{2}$ inches, the resisting powers will probably be increased to 850 or 900 lbs. on the square inch, that is, 7 or 8 times the working pressure.

On a careful examination of the fire-box and every other part of the boiler, it was found that the stays and copper were perfect, and that they were able to sustain a pressure much exceeding 207 lbs. upon the square inch, as given in the following table.

In these experiments, the top of the fire-box sank a little, owing to the breakage of a bolt of one of the cross-bars; but the fire-box stays were quite perfect, and to every appearance would have sustained nearly double that pressure. If the fire-box stays had been new and the top well-stayed, it is more than probable that a force from 800 to 900 lbs. on the square inch would have been required to cause rupture.

As much stress has been laid upon the weakness of the stays which unites the flat surface of the boiler to the sides of the fire-box, the fol-

* *Vide* Experiments, Note, p. lxxii.

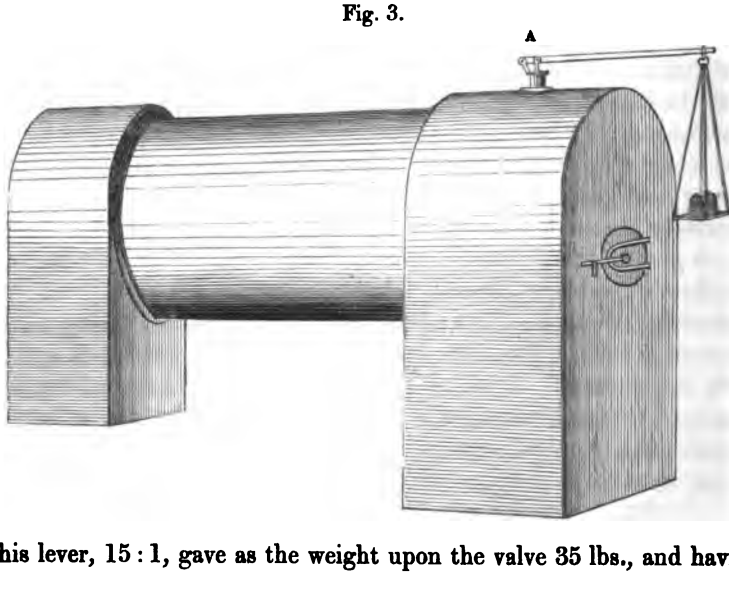
lowing experiments clearly indicate that the fire-box stays are not the weakest parts of a locomotive boiler, and that we have more to fear from the top of the furnace, which under severe pressure is almost invariably the first to give way. Great care should therefore be observed in the construction of this part, as the cross-beams should not only be strong, but the bolts by which the crown of the fire-box is suspended should also be of equal strength, in order that no discrepancy should exist, and that all the parts should be proportioned to a resisting force of at least 500 lbs. on the square inch.

Finding our knowledge with regard to the power of resistance of locomotive boilers to strain exceedingly imperfect, I availed myself of the present opportunity to determine by actual experiment the laws on which these powers are founded; and for this purpose the Directors of the London and North-Western Railway Company placed in my hands an engine of the same age, constructed by the same makers, and in every respect a fac-simile of that which exploded. This engine was subjected to hydraulic pressure as follows:—

Experiment made May 4th, 1853, *to determine the Resisting Powers of the Fire-box and Exterior Shell of No.* 2 *Engine on the Eastern Division of the London and North-Western Railway.*

In this experiment, the boiler was furnished with a valve, A, of exactly 1 inch area, and a lever of the annexed dimensions, as per sketch, fig. 3.

Fig. 3.



This lever, 15 : 1, gave as the weight upon the valve 35 lbs., and having

suspended the scale, which indicated with the lever 50 lbs., the following results were obtained:—

TABLE I.

Number of pounds on scale.	Weights per square inch upon the valve.	Remarks.
Lever	35·0	
Scale	50·0	This engine was the same age, and had run about the same number of miles as the exploded engine. The fire-box was considerably sunk or bulged, and the rivets as well as the stays much weakened. The engine had been at work since 1840.
½	57·5	
1	65·0	
1½	72·5	
2	80·0	
2½	87·5	
3	95·0	
3½	102·5	
4	110·0	With this pressure a leakage was observed at some of the joints.
4½	117·5	
5	125·5	
5½	132·5	
6	140·0	Leakage increased.
6½	147·5	
7	155·0	
7½	162·5	
8	170·0	Leakage still increasing.
8½	177·5	
9	185·0	
9½	192·5	
10	200·5	
10½	207·5	With this pressure one of the bolts of the cross-bar over the fire-box broke, which caused the experiment to be discontinued, as the leakage was greater than the force-pump could supply.

From the above, it is evident that the boiler which led to these experiments could not have burst under a pressure of less than 300 to 350 lbs. upon the square inch, as the failure of a single bolt in one of the cross-bearers above the fire-box, under a pressure of 207 lbs. on the square inch, was not the measure of its strength, but one of those accidental circumstances which is calculated to weaken, but not absolutely destroy its ultimate powers of resistance. I have been led to this conclusion from the fact of finding the upper part of the fire-box in every respect perfect. After the removal of the pressure of 207 lbs. on the square inch, and comparing these experiments with the appearance of the crown of the ruptured fire-box, I am confirmed in the opinion that steam of high elastic force must have been present to cause the disastrous explosion which eventually occurred.

Again referring to Mr. Ramsbottom's Report, he states,—"That it has been objected that the steam could not have been raised from 60 lbs. per square inch, the pressure at which the safety-valve was blowing off before being screwed down, to the pressure stated by Mr. Fairbairn in

twenty-five minutes; but although I do not go all the way with Mr. Fairbairn as to the strength of the boiler, I find, from experiments made upon a boiler of somewhat similar dimensions, and placed as nearly as possible under the same circumstances, that the steam was raised from 30 lbs. per square inch to 80 lbs., as shown by Bourdon's steam-gauge according to the following scale, namely,—

Safety-valve screwed down	3	1	20 = 30 lbs.	per square	inch.
... ...	3	2	30 = 35	...	...
... ...	3	3	45 = 40	...	...
... ...	3	5	00 = 45	...	...
... ...	3	6	15 = 50	...	...
... ...	3	7	20 = 55	...	...
... ...	3	8	30 = 60	...	...
... ...	3	9	30 = 65	...	...
... ...	3	10	30 = 70	...	...
... ...	3	11	30 = 75	...	...
... ...	3	12	20 = 80	...	..."

These experiments, although perfectly satisfactory as regards the time required to raise the steam (under ordinary circumstances of the engine, standing with the fire lighted, and the usual quantity of coke in the furnace) from 30 up to 80 lbs. on the square inch—it was nevertheless considered desirable to repeat them through a still higher scale of pressure and temperature, and to ascertain, not only the exact time, but the ratio of increase, and the corresponding temperature of the steam in the boiler as the pressure progressively increased. For these objects, two delicately constructed thermometers were prepared by Mr. Dalgetti, and having adjusted Bourdon's pressure-gauge by a corresponding column of mercury, and an engine having been placed at my disposal, the following results were obtained:—

Experiment made May 7th, 1853, *to determine the rate of Increased Pressure, Temperature of Steam, &c. in a Locomotive Engine with the Safety-valve screwed down and the Fire under the Boiler.*

TABLE II.

Time.	Pressure.	Temperature, No. 1 gauge.	Temperature, No. 2 gauge.	Mean temperature.	Remarks.
h m					
2 44	11·75	243°	243°	243·00°	
2 45	14·15	247	246½	246·75	
2 46	16·35	251	251	251·00	
2 47	19·25	255½	255	255·25	
2 48	22·35	260	259½	259·75	
2 49	25·75	264	264	264·00	
2 50	28·95	268½	268¼	268·37	
2 51	32·15	273	273	273·00	
2 52	35·75	277	277	277·00	
2 53	39·95	282	282	282·00	
2 54	44·25	286½	286¼	286·37	
2 55	48·35	291	291	291·00	
2 56	52·75	295½	295¼	295·37	
2 57	57·75	300	300	300·00	
2 58	63·75	304¼	304¼	304·25	
2 59	68·95	308½	309	308·75	
3 00	74·75	313	313	313·00	
3 01	80·35	318	317½	317·75	
3 02	87·25	322	322	322·00	
3 03	93·95	326¼	326	326·12	
3 04	101·15	331	331	331·00	
3 05	108·75	335½	335¾	335·62	
3 06	111·75	......	......	......	This experiment was lost, the thermometers not indicating a higher temperature.

Let us now endeavour from this table to discover the law expressing the relation between the time and pressure, or between the time and temperature*.

The observations being made at intervals of one minute of time, and the furnace being maintained at the same intensity, it may be presumed that the quantity of heat communicated to the water was uniform, or that there were equal quantities of absolute heat communicated to the boiler in equal times.

The column of pressures gives the successive augmentations of pressure at equal intervals, and the column of temperatures gives the corresponding augmentations of heat as indicated by the thermometer.

The column of pressures shows that the increments of pressure, in equal intervals of time, increase with the temperature; thus at or near 260° the average increment of pressure is at the rate of 3·1 lbs. per

* I am indebted to my friend Mr. Tate for the mathematical analysis of this question.

minute; at or near 282°, it is 5·4 lbs. per minute; and at or near 326°, it is 7·1 lbs. per minute.

Mr. Ramsbottom's table of experiments indicates a similar result; thus at or near 268° the average increment of pressure is at the rate of 4 lbs., whereas at or near 304° it is at the rate of 5 lbs. per minute.

The law, therefore, expressing the relation of time and pressure does not appear to admit of assuming a simple form. But the case is different with respect to the law expressing the relation of time and temperature. Thus if T = temperature in degrees, and t = the time in minutes at which this temperature is observed, estimated from the commencement of the experiments, then

$$T = a \times t + b \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (1)$$

will give the relation betwen T and t with great precision where a and b are constants, whose values, derived from these experiments, are $a = 4{\cdot}44$ and $b = -486$.

For example, let $t = 166$, then

$$T = 4{\cdot}44 \times 166 - 486 = 251°,$$

which exactly corresponds with the tabular value.

Again, let $t = 180$, then

$$T = 4{\cdot}44 \times 180 - 486 = 313{\cdot}2;$$

in this case the tabular value is 313°.

Again, let $t = 185$, then

$$T = 4{\cdot}44 \times 185 - 486 = 335°{\cdot}4;$$

in this case the tabular value is 335°·6.

From this formula we find

$$t = \frac{T + 486}{4{\cdot}44} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (2)$$

If $t_{\prime}$ = the number of minutes which elapse between the temperatures T and $T_{\prime}$, then we find from 29 (1),

$$T_{\prime} - T = 4{\cdot}44 t_{\prime}; \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (3)$$

which shows that *the temperature increases with the time*; and presuming that the heat of the furnace remained constant, this formula also shows that *equal increments of absolute heat produced equal increments of sensible temperature as indicated by the thermometer.*

To determine the time, estimated from a given pressure, at which the boiler would burst,—

1st. Let the given pressure be that of the atmosphere, and let the boiler be able to sustain 240 lbs. pressure per square inch.

From an experimental table of pressures and temperatures, we find

240 lbs. pressure to correspond to 403° temperature, and 15 lbs. pressure to 212° temperature; hence we have by formula (3),

$$t_{,}-=\frac{403-212}{4\cdot44}=43 \text{ minutes},$$

which is the time in which the boiler would burst, estimated from the time at which the water begins to boil.

2nd. Let the given pressure be 60 lbs. per square inch, and the boiler-pressure 240 lbs. per square inch, then

$$t_{,}=\frac{403-296}{4\cdot44}=24\cdot1 \text{ minutes}.$$

3rd. Let the given pressure be 60 lbs. per square inch, and the boiler-pressure 300 lbs., then

$$t_{,}=\frac{422-296}{4\cdot44}=28 \text{ minutes},$$

which is nearly the time in which the boiler experimented upon would burst.

These facts appear to be sufficiently conclusive to enable us to judge of the dangers to which people expose themselves under circumstances where the necessary precautions are not taken for allowing the steam thus generated with the fire under the boiler to escape. The great majority of accidents of this kind have arisen during the time the engines are standing, probably with the safety-valve fastened and a brisk fire under the boiler. How very often do we find this to be the case in tracing the causes of these melancholy and unfortunate occurrences!

The statements contained in the earlier part of this paper regarding the strength of the stays of the fire-box would have been incomplete if we had not put those parts of a locomotive boiler, comprised in the flat surfaces or sides of a fire-box, to the test of experiment.

This was done with more than ordinary care; and in order to attain conclusive results, two thin boxes, each 22 inches square and 3 inches deep, were constructed; the one corresponding in every respect to the sides of the fire-box, distance of the stays, &c., the same as those which composed the exploded boiler; and the other formed of the same thickness of plates, but different in the mode of staying, which in place of being in squares of 5 inches asunder, as those contained in the boiler which burst, were inserted in squares of 4 inches asunder. In fact, they were formed as per annexed sketch (figs. 4 and 5), the first containing 16 squares of 25 inches area, and representing the exploded boiler, or old construction; and the other, with 25 squares of 16 inches area, representing the new construction.

Fig. 4.

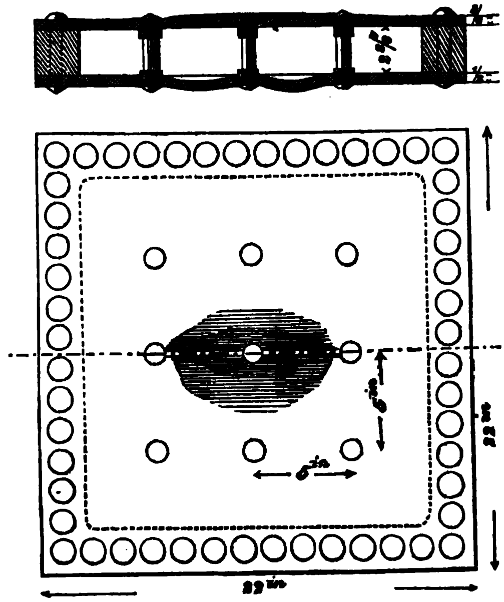
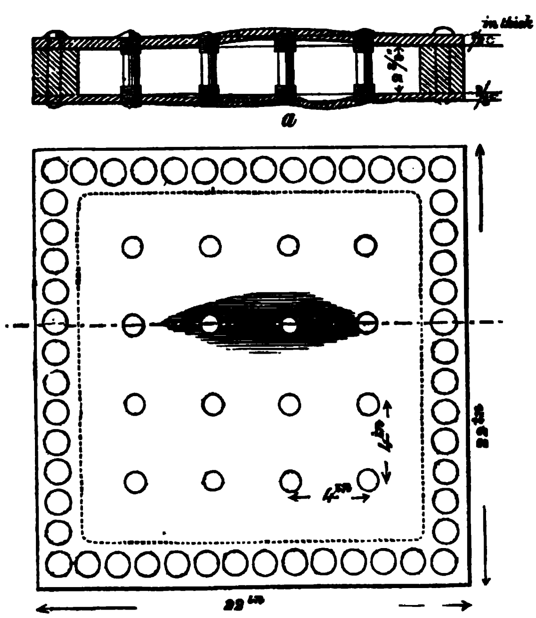


Fig. 5.



To the flat boxes thus constructed, the same lever, valve, and weight were attached as used in the previous experiments; and having applied the pumps of a hydraulic press, the following results were obtained:—

TABLE III.

Experiment 1st.—To determine the ultimate Strength of the Flat Surfaces of Locomotive Boilers when divided into squares of 25 inches area.

Number of experiments.	Pressure in pounds per square inch.	Swelling of the sides in inches.	Remarks.
1.	245	+	
2.	275	+	
3.	305	+	
4.	335	+	The box representing a portion of the flat surface of the side of the fire-box of a locomotive boiler was composed of a copper plate, on one side half an inch thick, and an iron plate on the other three-eighths of an inch thick, being the same in every respect as the boiler which exploded, and according to the dimensions exhibited in the drawings, fig. 4.
5.	365	+	
6.	395	+	
7.	425	+	
8.	455	·03	
9.	485	·03	
10.	515	·04	
11.	545	·05	
12.	575	·05	
13.	605	·06	
14.	635	·06	
15.	665	·06	
16.	695	·07	
17.	725	·07	
18.	755	·07	
19.	785	·08	
20.	815	...	Burst by drawing the head of one of the stays through the copper, which from its ductility offered less resistance to pressure in that part where the stay was inserted.

The above experiments are at once conclusive as to the superior strength of the flat surfaces of a locomotive fire-box, as compared with the top, or even the cylindrical part of the boiler; but taking the next experiment, where the stays are closer together, or where the areas of the spaces are only 16 instead of 25 square inches, we have an enormous resisting power; a force much greater than anything that can possibly be attained, however good the construction, in any other part of the boiler.

Table IV.

Experiment 2nd.—To determine the ultimate Strength of the Flat Surfaces of Locomotive Boilers when divided into squares of 16 inches area.

Number of experiments.	Pressure in pounds per square inch.	Swelling of the sides in inches.	Remarks.
1.	245		
2.	275		
3.	305		
4.	335	...	The flat box on which these experiments were made has the same thickness of plates as that experimented upon in the preceding table, viz. one side of copper half an inch thick, and the other of iron three-eighths thick. The only difference between the two is the distance of the stays, the first being in squares of 25 inches area, and the other in squares of 16 inches area.
5.	365		
6.	395		
7.	425		
8.	455		
9.	485		
10.	515	·04	
11.	545	·04	
12.	575	·04	
13.	605	·06	
14.	635	·06	
15.	665	·07	
16.	695	·07	
17.	725	·07	
18.	755	·08	
19.	785	·08	
20.	815	·08	
21.	845	·08	
22.	875	·08	
23.	905	·08	
24.	935	·08	
25.	965	·09	
26.	995	...	From 995 to 1295 lbs., the swelling or bulge on the side was inappreciable.
27.	1025		
28.	1055		
29.	1085		
30.	1115		
31.	1145		
32.	1175		
33.	1205		
34.	1235		
35.	1265		
36.	1295	·09	
37.	1325	·09	
38.	1355	·10	
39.	1385	·11	
40.	1415	·11	
41.	1445	·12	
42.	1475	·13	
43.	1595	·14	
44.	1535	·16	
45.	1565	·22	
46.	1595	·34	
47.	1625	...	Failed by one of the stays drawing through the iron plate after sustaining the pressure upwards of 1½ minute.

In the above experiments, it will be observed that the weakest part of the box was not in the copper, but in the iron plates, which gave way

by stripping or tearing asunder the threads or screws in part of the iron plate at the end of the stay marked *a*, fig. 5.

The mathematical theory would lead us to expect that the strength of the plates would be *inversely as the surfaces between the stays*; but a comparison of the results of these experiments shows that the strength decreases in a higher ratio than the increase of space between the stays. Thus, according to the mathematical theory, we should have—

$$\text{Ult. strength 2nd plate per sq. in.} = \text{strength 1st plate} \times \tfrac{25}{16}$$
$$= 815 \times \tfrac{25}{16} = 1273 \text{ lbs.}$$

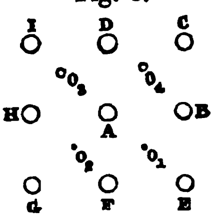
Now this plate sustained 1625 lbs. per square inch, showing an excess of about one-fourth above that indicated by the law.

This is in excess of the force required to strip the screw of a stay $\frac{11}{16}$ths of an inch in diameter, such as those which formed the support of the flat surfaces in the exploded boiler.

It will be found that a close analogy exists throughout the whole experiments, as respects the strengths of the stays when screwed into the plates, whether of copper or iron; and that the riveting of the ends of the stays adds to their retaining powers an increased strength of nearly 14 per cent. to that which the simple screw affords. The difference between a fire-box stay when simply screwed into the plate and when riveted at the ends is therefore in the ratio of 100 : 76, nearly the same as shown by experiment in the Appendix.

It is desirable, therefore, that we should ascertain the strain exerted on each stay or bolt of the fire-box.

Fig. 6.



Let A, B, C, D, E, F represent the ends of the bolts or stays; O_1, O_2, O_3, O_4 the centres of the squares formed by the bolts. Suppose a pressure to be applied at each of the points O_1, O_2, O_3, O_4 equal to the whole pressure on each of the squares, then the central bolt A will sustain one-fourth of the pressure applied at O_1, also one-fourth of the pressure applied at O_2, and so on; so that the whole pressure on A will be equal to the pressure applied to one of the square surfaces. Hence we have—

$$\text{Strain on the stay of Table III.} = \frac{815 \times 25}{2240} = 9 \text{ tons.}$$

$$\text{Strain on the stay of Table IV.} = \frac{1625 \times 16}{2240} = 11\tfrac{1}{2} \text{ tons nearly.}$$

The stay in the latter case was $\frac{13}{16}$ths of an inch in diameter; hence the strain upon one square of section would be about 13 tons, which is

considerably within the limits of rupture of wrought iron under a tensile force.

In the experiments here referred to, it must be borne in mind that they were made on plates and stays at a temperature not exceeding 50° of Fahrenheit; and the question naturally occurs, as to what would be the difference of strength under the influence of a greatly increased temperature in the water surrounding the fire-box, and that of the incandescent fuel acting upon the opposite surface of the plates.

This is a question not easily answered, as we have no experimental facts sufficiently accurate to refer to; and the difference of temperature of the furnace on one side, as compared with that of the water on the other, increases the difficulty, and renders any investigation exceedingly unsatisfactory. Judging, however, from practical experience and observation, I am inclined to think that the strengths of the metals are not much deteriorated. My experiments on the effects of temperature on cast iron * do not indicate much loss of strength up to a temperature of 600°. Assuming therefore that copper and wrought iron plates follow the same law, and taking into account the rapid conducting powers of the former, we may reasonably conclude that the resisting powers of the plates and stays of locomotive boilers are not seriously affected by the increased temperature to which they are subject in a regular course of working. This part of the subject is, however, entitled to future consideration; and I trust that some of our able and intelligent superintendents will institute further inquiries into a question which involves considerations of some importance to the public, as well as to the advancement of our knowledge in practical science.

Note.

In order to test with accuracy the tensile power of the different descriptions of stays used in locomotive boilers, and to effect a comparison between those screwed into the plates and those both screwed and riveted, it was deemed expedient to repeat Mr. Ramsbottom's experiments on a larger scale; and by extending the tests to copper stays as well as iron ones, it was considered that no doubt could exist as to the ultimate strength of those simply screwed, the tensile powers of the stays themselves, and the relative difference between those and the finished stays when screwed and riveted on both sides of the fire-box.

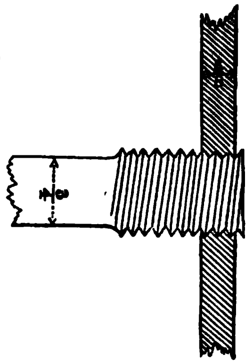
The large lever and requisite apparatus being at hand, the experiments proceeded as follows:—

* *Vide* the Transactions of the British Association for the Advancement of Science, vol. vi. p. 406.

Experiments to determine the Ultimate Strength of Iron and Copper Stays generally used in uniting the flat surfaces of Locomotive Boilers.

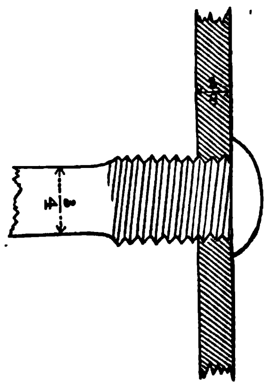
EXPERIMENT I.—Iron Stay, $\frac{3}{4}$ths of an inch in diameter, screwed into a copper plate $\frac{5}{8}$ths of an inch thick.

No. of experiment.	Weight in pounds.	Remarks.
Lever 1.	9,860	With the last weight, 18,260 lbs.=8·1 tons, the threads in the copper plate were drawn out or stripped after sustaining the weight a few seconds.
2.	11,540	
3.	13,220	
4.	14,900	
5.	16,580	
6.	18,260	



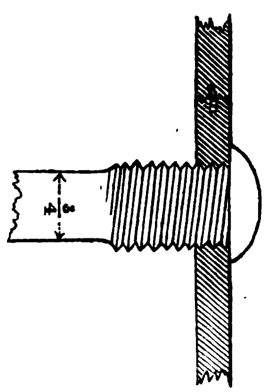
EXPERIMENT II.—Iron Stay, $\frac{3}{4}$ths of an inch in diameter, *screwed and riveted* into a copper plate $\frac{3}{8}$ths of an inch thick.

No. of experiment.	Weight in pounds.	Remarks.
Lever 1.	9,860	
2.	11,540	
3.	13,220	When the last weight, 24,140 lbs. =10·7 tons, was laid on, the head of the rivet was torn off; and the stay, along with the threads in the copper, was drawn through the plate.
4.	14,900	
5.	16,580	
6.	18,260	
7.	19,940	
8.	21,620	
9.	23,300	
10.	24,140	

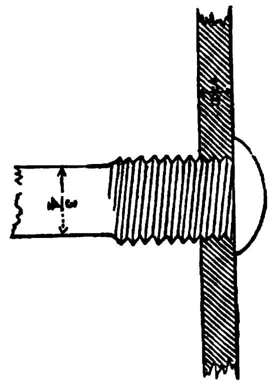


EXPERIMENT III.—Iron stay, $\frac{3}{4}$ths of an inch in diameter, *screwed and riveted into an iron plate* $\frac{3}{8}$ths of an inch thick.

No. of experiment.	Weight in pounds.	Remarks.
Lever 1.	9,860	
2.	13,220	
3.	16,580	
4.	19,140	With the last weight, 28·760 lbs. =12·5 tons, the stay was torn asunder through the middle, both screw and plate remaining perfect.
5.	20,780	
6.	23,300	
7.	25,980	
8.	26,660	
9.	27,940	
10.	28,760	



EXPERIMENT IV.—Copper Stay, ¾ths of an inch in diameter, screwed and riveted into a copper plate ⅝ths of an inch thick.



No. of experiment.	Weight in pounds.	Remarks.
Lever 1.	9,860	With 11,540 lbs. the body of the stay was slightly elongated.
2.	11,540	
3.	13,220	Elongation considerably increased with 14,900 lbs.
4.	14,900	
5.	16,265	Broke with 16,265 lbs. = 7·2 tons, after sustaining the load upwards of three minutes.
		Ultimate elongation, 0·56 inch in a length of 3 inches.

It will be observed, on comparing the results obtained from the above experiment, that iron plates and iron stays are considerably stronger than those made of copper. It may not be advisable to have the interior fire-box made of iron, on account of its inferior conducting powers and its probable durability; but so far as regards strength, it is infinitely superior to that of copper, as may be seen by the following

Summary of Results.

No. of experiment.	Breaking weight in tons.	Resistance per square inch in tons.	Ratio, Experiment III., the iron stay and iron plate taken as 1000.
III.	12·5	27·7	1000 : 1000 Iron and iron.
I.	8·1	18·8	1000 : 648 Iron and copper screwed.
II.	10·7	23·6	1000 : 856 Iron and copper screwed and riveted.
IV.	7·2	16·1	1000 : 576 Copper and copper screwed and riveted.

On the above data, it will be found that the iron stay and copper plate (not riveted) have little more than one-half the strength of those where both are of iron; that iron stays screwed and riveted into iron plates are to iron stays screwed and riveted into copper plates as 1000 : 856; and that copper stays screwed and riveted into copper plates of the same dimensions, have only about one-half the strength of those where both the stays and plates are of iron. These are facts in connexion with the construction of locomotive, marine, and other description of boilers having flat surfaces, which may safely be relied upon, and that more particularly when exposed to severe strain, or the elastic force of high-pressure steam.

APPENDIX III.

Boiler Explosion at Rochdale, July 1854.

In accordance with instructions received from the coroner and jury in this case, I visited the scene of the accident on Monday last, and having made a careful inspection of the debris which covers the premises, site of boiler, steam-engine, &c., I have now to report as follows:—With the exception of some parts of the boiler and fragmental parts of the machinery, which had been removed when searching for the bodies of those killed, I found the buildings, steam-engine, boiler, and machinery, a heap of ruins. The boiler was torn into eight or ten pieces, one portion (the cylindrical part) flattened and imbedded at a considerable depth in the rubbish, and the two hemispherical ends burst asunder and driven in opposite directions to a distance of 30 to 35 feet from the original seating of the boiler. Other parts of the cylinder and ends were projected over the buildings across Gashouse Lane, and lodged in a field, at a distance of 90 yards from the point of projection. To one of these parts was attached the 2-inch safety-valve, which was torn from the boiler by the force of the explosion, and carried along with its seating over a rising ground to a distance of nearly 250 yards. The other portion of the cylindrical part of the boiler was found on the opposite side in the bed of the river, and the hemispherical end of this part (furthest from the furnace) was rent in two, and thrown on each side to a distance of 30 or 35 feet. These two pieces had evidently come in contact with the chimney, razed it to the ground, and finally lodged themselves on the margin of the river. The 3-inch safety-valve and pipe attached to that portion of the boiler imbedded in the river was broken from the flange, and with an extended range the 2-inch valve was projected over the river into a meadow at a distance of 150 to 200 yards. Of the steam-engine there is not a vestige to be seen, except the fly-wheel, and a pump-rod which lies beside it, covered with bricks. This was the state in which I found the remains of the boiler and steam-engine, and looking at the havoc done to the premises, the complete demolition of the buildings, the fall of the chimney, and the force of the projectiles, it is evident that the density of the steam must have been much beyond the ordinary working pressure of 50 lbs. to 60 lbs. on the square inch. It would seem from the position of the different fragments, and the appearance of the end of Mr. Bottomley's mill (which is covered with the sediment of the steam and water), that the boiler, or the cylindrical part of

it, must have risen vertically; or rather, that the forces at the moment of rupture must have acted from a common centre, driving the hemispherical ends in opposite directions, tearing open the body with a force that would raise it vertically; and having encountered the buildings and other resistances, would again descend almost close to the spot from whence it was projected. The springing of a mine could not have been more destructive than this explosion, which resulted in the tearing of the boiler into strips, and the destruction of everything with which it came in contact. In attempting to arrive at the force of the explosion, the jury will probably bear with me whilst I endeavour to trace the cause which led to this deplorable accident. The task is surrounded with some difficulties, such as the want of an accurate knowledge of the state of the safety-valves; the density of the steam at the moment of rupture; the ultimate strength of the boiler, &c.;—and I shall have to enter a little into detail, and make a few comparisons which I trust may be useful to those entrusted with the management of boilers and the employment of steam of increased density and great elastic force. It has been calculated that gunpowder impels a body before it with a force 244 times greater than the pressure of the atmosphere, which, taken at 15 lbs., gives $244 \times 15 = 3660$ lbs. as the force upon a square inch of surface. This would give nearly 30 tons upon a piece of ordnance of 6 inches calibre; but to this must be added the augmentation of elastic power derived from the heat generated in firing gunpowder, which raises it up to $999\frac{1}{5}$ or 1000. Atmospheric bullets discharged with this force, or rather with a proportionate charge of powder, will leave the muzzle of the piece at a velocity of 1700 feet per second, or nearly 20 miles a minute. Now, if we compare this with steam at 300 lbs. on the square inch (which I find is about the bursting pressure of the exploded boiler), we shall find that, however disastrous the effects of boiler explosions containing high steam may be, they are not to be compared—although sufficiently appalling—with gunpowder as an agent of destruction. I have made this comparison to show that steam and steam-boilers, although not so dangerous as gunpowder, are nevertheless sufficiently so to be placed in the category, and ought to be treated in the same manner, and with the same precaution. In the question before us, I find the boiler with hemispherical ends 18 feet long, 5 feet diameter, and composed of plates $\frac{5}{16}$ths of an inch thick, (*a*) to be equal in its powers of resistance to a pressure of 335 lbs. on the square inch; but finding one of the plates under $\frac{5}{16}$ths in thickness, I have reduced its power to 300 lbs., which I consider the force at which it would burst. Now, if we take 300 lbs. as the pressure exerted against every square inch of its surface, and its superficies at 41,000 inches, we

have pent up in this comparatively small vessel the enormous force of 41,000 + 300 = 12,300,000 lbs.; or 5491 tons of elastic force enveloped in an iron case of little more than ¼th of an inch in thickness. A knowledge of this fact would appear to be sufficient to place people upon their guard as to the dangers to be encountered by tampering with an agent of such mighty power as imprisoned steam. The relative volume of steam at the pressure of the atmosphere is 1700 times that of water, at higher temperatures and increased density the volume is reduced in a given ratio of its temperature and density; and it is also observed, that, when steam is generated in a boiler, the temperature increases with the pressure, and *vice versâ* the pressure increases with the temperature. It is impossible therefore to increase the temperature without increasing the pressure. In this state, therefore, steam is at its maximum of density or pressure when compared with its temperature. This correspondence of temperature and pressure only arises when the steam is in the boiler with a sufficient quantity of water to supply the quantity generated or given off to the engine. At other times, when the communication with the boiler is cut off, the maximum ceases for want of water to supply the quantity carried off, and which is necessary to increase the pressure*. Knowing these facts, it will be seen that in boilers having an active fire burning under them, the engine standing, and the safety-valves fast (it matters not how), the temperature will rise, the pressure increase, and explosion ensue, unless relieved by starting the engine or letting off this dangerous accumulation of temperature and pressure. How careful ought we therefore to be, to look to the valves, to regulate the fires, and to keep down the pressure below the dangerous point of resistance; and how very serious the responsibility, when either from ignorance or neglect, the force is allowed to accumulate beyond all powers of resistance! Steam-boilers of every description should be constructed of sufficient strength to resist eight times the working pressure; and no boiler should be worked under any circumstances whatever unless provided with at least two—I would prefer three—sufficiently capacious safety-valves. Two of these valves should be nearly equal to double the area of the steam ports of the engine they are intended to drive, and the other about one-fourth that area as an indicator of the pressure. These provisions made, I would, under public sanction, determine that no steam-boiler, of whatever description, should be used without them; and these again, when properly applied, should be placed in the hands of the proprietor intending to work them, and whether ignorant or conversant with the

* These facts have been ably discussed by Comte de Pambour, in his treatise on locomotive engines.

subject he should be made responsible, and that to the fullest extent. In the present instance, I believe that both Mr. Williamson and his engineer are ignorant of the properties of steam, and the care that is necessary for retaining it within bounds of control (*b*). This is, however, no excuse for the accident that has occurred, or for the neglect on the part of the engineer in allowing his safety-valves to get out of order, and for the losses ultimately sustained by families who now mourn the loss of their relatives and friends. In this case, any more than in others I have been called upon to investigate, I am not advocating the interference of the legislature, but I strongly suspect that that interference is more than likely to take place, unless greater precautions are taken to protect the lives and limbs of the community (*c*). It has been my duty, on several occasions, to make appeals to the proprietors and owners of steam-engines, urging them to do for themselves what the government will assuredly do for them; and unless appointments are made, and greater precautions taken to enforce closer attention, and effect greater security to their work-people, it will become the duty to do by law what, in my opinion, should be done without it (*d*). To the numerous boiler accidents which from time to time have occurred in these districts, may be traced the fact that nearly the whole of them have occurred when the engine is standing, or rather just after starting. Now this cannot be too generally known; and I take this opportunity of stating that nine-tenths of the accidents which occur are attributable to this cause, and may be prevented by a very moderate share of attention. In the first place, it must be understood that we cannot leave a blazing fire under a boiler with impunity, and that more particularly when the safety-valves are either of imperfect construction, fastened down, or accidentally shut. The generated steam and accumulated pressure under these circumstances must have vent; and in case it cannot escape through the engine, or out at the safety-valves, it is clear to make way for itself, not through the usual outlets, but through the sides, ends, or bottom of the boiler. That is the only outlet when the others are closed for the steam to escape. Engineers, millowners, &c. should never forget this tendency of imprisoned steam to rupture everything before it, and provided they had these dangers constantly before their eyes, it is more than probable we should seldom or never hear of boiler explosions.

As respects the relative volume of steam, as compared to the volume of water that produced it under pressure, it will be observed, on consulting the experiments of Arago and Dulong, that the volume bears a fixed relative proportion to the temperature and pressure, and that this steam, when reduced to the temperature of 212°, will occupy a space of 1700 times that of the water which produced it; and hence

follows an expansive force, at 119 lbs., of more than seven times its volume, and at 300 lbs. (the assumed bursting pressure of the boiler), at more than double that amount. Taking therefore into account not only the temperature of the steam, but the temperature of the water in the boiler, it would appear at the moment of rupture, that the force or actual quantity of steam would be augmented by dilatation, and the projecting power would thus be continued, until the original impetus was destroyed by the retarding masses with which it came in contact. Again, all the heat transmitted from the fire to the water in the boiler being retained in great force, that force is increased and rendered active by any disturbance, such as the starting of the engine, condensation, or any other cause which may affect the equilibrium of the pressure. It is therefore important that we should know these facts, that we should know how to apply them to our use with prudence and caution, and not to allow a practice, founded on an ignorance of the elements with which we have to deal, any longer to exist. It has been remarked, and closely argued by its advocates, that explosive gas is generated in several cases where these accidents occur. Now I utterly repudiate this notion, as I am satisfied, from observation and long practice, that gas has nothing to do with them,—that they are governed by a fixed and determined physical law, and that law is neither more nor less than excessive pressure. It is true, that in cases where boilers explode from want of water, and the plates become red-hot, then, and only then, does the spheroidal system of Boutigny come into operation, when large globules of water, containing immense central heat, are formed, and bursting with great force and a loud report, might rupture the vessel in which they are contained. This cannot, however, take place unless water is pumped into the boiler suddenly, and without reflection as to the results. Altogether, I am of opinion that these sort of accidents seldom if ever occur. The contrary is almost invariably the case, and boiler explosions, although varied in conditions and circumstances, are nevertheless traceable to that undeviating law of pressure which invariably becomes the destructive when allowed to exceed the resisting powers of the vessel in which it is contained. I have already described the force, the direction, and the consequent effects of the explosion; but I have not as yet given a decided opinion as to what I consider to be the ultimate cause of the explosion. I have endeavoured to arrive at this by a close investigation of the state of the safety-valve, and taking into consideration the slovenly and careless manner in which these important adjuncts had been treated, I am not surprised that they should fasten themselves and totally prevent the escape of the surcharged steam. The 2-inch valve I find was held down by two weights,—one 24 lbs., at the extreme end of the lever,

and the other $22\frac{1}{2}$ lbs. at about half the distance from the fulcrum; calculating the pressure due to these weights, we have about 76 lbs. on the square inch (*e*). What the 3-inch valve had upon it I am unable to determine, as the weights have not been found; I have, however, examined the valve very minutely, and find that the spindle which passes through a hole in the cover, is rather tight; and looking at the rusty state in which I found it, I have no hesitation in stating that it was inoperative, and, independent of the weight upon the lever, had got fast in the hole. The load upon the 2-inch valve was an excess of pressure for such a boiler, but I do not consider that such a load would have proved fatal provided the other valve had worked freely and had not been overloaded. In a word, I am satisfied there was no escape for the steam for some time previous to the starting of the engine, and the boiler being at the point of rupture, the least disturbing cause was sure to terminate in the results on which I have been called upon to report.

(*a*) One part of the boiler, I am told, was of $\frac{3}{8}$-inch plates; but it is immaterial how thick one part may be, for the thinner part is the measure of the strength of a boiler.

(*b*) I do not of course speak here of Mr. Williamson individually, or with any intention of prejudicing him in the minds of the jury. I know that there are a great many people who use steam-boilers, and who are not at all acquainted with the dangers that surround them: I speak generally, with reference to what is necessary to be observed in the working of all steam-boilers.

(*c*) The frequent recurrence of these lamentable accidents seems to me to be very likely to cause the enactment of some stringent laws for the protection of the lives of all those exposed to such catastrophes.

(*d*) It appears to me that it is possible, and quite practicable, to establish an association (for instance) in Rochdale and the surrounding districts, the members of which should appoint one or two inspectors to take cognizance of all the boilers in the district, and to report to the association, weekly, in what state they found the boilers, and why they were not in a working condition, if the inspector or inspectors thought such to be the case. I do not think it would be any tax on the proprietors of boilers to pay a trifling sum yearly to meet the expenses of such an association; for it strikes me forcibly that we should not only avoid these very serious accidents, but I believe it would be productive of benefit to the proprietors, and save a great deal of money which is now lost by the frequent explosions.

(*e*) If there was an 8 lb. weight in addition upon this 2-inch valve, of which I was not informed [but which Clegg, the engine tenter, stated

in his evidence that he worked with, although he took it off on the night before the explosion, as was his custom, to allow the steam to escape], that would give something like 9 lbs. pressure extra. I could not, on Monday, learn the weight that was upon the 3-inch valve, but I find that it had an iron cover, with an iron spindle working through it. There seemed to be room for just sufficient motion of the spindle to make the valve act; and I could not lift it more than one eighth of an inch before it got fast. But the least dampness, from the steam or otherwise, would cause the iron to rust, so that it would become jammed, and all the pressure you could bring to bear upon it would never move it. I certainly do not think that this valve was in action on the morning of the explosion. It would be much better that covers and spindles should be of brass, which is not so likely to oxidize. This valve might, under many circumstances, work freely; but it might also stick fast at the very moment it was most wanted. Under all the circumstances, I have no hesitation in saying that this valve must have been fast at the time of the explosion. I do not think that the boiler could have exploded, if the valve had been working and had not been overweighted: I mean, if there had not been a greater pressure upon it than that upon the 2-inch valve. [The Coroner read the evidence of the lad Samuel B. Taylor, as to the putting of an extra loom-weight upon the 2-inch valve, a few minutes before the explosion; and Mr. Fairbairn said that this valve must have then been weighted up to 150 lbs. or even 180 to 200 lbs. on the square inch. Even supposing the 2-inch valve to have been in working condition, he was not sure that it would have sufficiently relieved the boiler of the rapidly-accumulating steam, and prevented the explosion.]

Verdict of the Jury.

At half-past seven the jury were left to consider their verdict. They remained locked up until one o'clock yesterday (Friday) morning; when the foreman handed to the Coroner the following verdict:—

"That, in the opinion of the jury, the death of Ann Stott and nine other persons was caused by an explosion of the boiler, at Bridgefield Mill, occupied by George Williamson, such explosion being occasioned by an excessive pressure of steam, and that pressure being produced by the following circumstances:—first, the 3-inch safety valve not being in working order, and consequently inactive; secondly, the 2-inch safety valve being, on the morning of the explosion, much overweighted; and thirdly, as the engine only worked at intervals from six o'clock to twenty minutes past, a space of time elapsed during which the fire was kept up, and in that time such an amount of heat was added to the water in the

boiler, and pressure thereby accumulated, as to render it impossible that the boiler could be relieved by the small or 2-inch valve when so overweighted. The jury at the same time wish to express their opinion that the boiler and engine at Bridgefield Mill were very improperly managed, thereby causing danger to the parties employed; and that the occupier and engineer are exceedingly blameable for working the boiler at the high pressure they have done for a long time previous to the explosion."

We understand that the jury appended to their verdict the following remarks:—

"The jury cannot separate without pressing on the consideration of the owners and users of steam boilers throughout the kingdom, the necessity there is that measures should be taken by them to ensure a thorough and frequent inspection of boilers, so as to prevent, as far as human care can, the recurrence of explosions; and they would recommend that for this purpose the owners, &c. in various districts should meet and appoint their own inspectors, who should grant certificates respecting the working, &c. thereof in the districts as such inspectors might be appointed; they (the jury) believing that by such appointment and control a direct benefit would ensue, as well as the advantage of preventing other interference."

APPENDIX IV.

Association for the Prevention of Steam Boiler Explosions, and for effecting Economy in the Raising and Use of Steam.

RULES.

1. That the association be called "The Association for the Prevention of Steam Boiler Explosions, and for effecting Economy in the Raising and Use of Steam."

2. That all persons employing steam power within a circuit of 35 miles round Manchester, be eligible as members.

3. That this circuit be divided into districts, with power to enlarge the sphere of the association by the addition of new districts, contiguous to the circuit now defined, when sufficient local support is offered and the approval of a general meeting obtained.

4. That the management of the business of the association be entrusted to a committee, consisting of six members, representing Man-

chester and its immediate neighbourhood, and two members from each district; a president, and four vice-presidents, *ex officio* members of the committee. Three to be a quorum.

5. That the committee of management be elected annually at a general meeting, to be held on the last Tuesday in November in each year.

6. That all questions, whether at the general or committee meetings, be decided by a vote of the majority of the members present, each firm to have one vote, and the chairman a casting vote.

7. That no firm, whose subscription is in arrear, have the privilege of voting.

8. That the president, or one of the vice-presidents, when present, occupy the chair.

9. That the expenses of the association be met by an entrance fee of £2, and of an annual subscription (payable in advance in the month of December in each year) for each steam-boiler in regular use. The first subscription to be 30*s*. per boiler, and the rate from November next for future years to be annually fixed by the general meeting.

10. That the committee shall appoint and dismiss all officers and others required to carry out the objects of the association, fix their respective salaries, and prescribe all rules and regulations for their guidance and observance.

11. That the office of the association be in Manchester, and be superintended by a secretary, who, with an assistant, shall have the custody of all documents and books belonging to the association, conduct the correspondence, record the proceedings, and receive, classify, and enter all reports and information for reference.

12. That the duty of visiting and inspecting the steam-engines, boilers, and furnaces of the members be discharged by a competent engineer, to be appointed as chief inspector, and one resident sub-inspector in each district, to act under the orders and supervision of the chief inspector.

13. That the sub-inspectors be elected or approved by a majority of the members in the districts to which they are appointed.

14. That the duty of the sub-inspectors be to visit periodically the steam department in the establishments of the members in their respective districts, to examine the steam boilers' safety valves, feed apparatus, and other parts on which safety depends, and with the permission of the proprietors to indicate the steam engines, note the duty performed, the steam pressure, and the fuel consumed, and to report the information obtained in writing, according to certain prescribed forms, to the chief inspector, with such observations as each inspection calls for.

15. That the chief inspector visit periodically the works of the members in each district in succession, and, in conjunction with the sub-

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inspector, examine the boilers and furnaces and all apparatus pertaining thereto, and call attention to such points as are susceptible of improvement.

16. That the chief inspector attend on the special summons in writing of any member to test the strength of boilers, the loading of safety valves, and the pressure of steam, or other special duties, for which service an extra charge shall be made to such member, according to a scale fixed by the committee.

17. That, in all cases of inspection, as also when the inspector has been summoned to test a boiler, or for other special purpose, he is to send to the secretary within forty-eight hours a written report of his visit, specifying the facts and the results of the case, which report the secretary is to inscribe in the record of the inspector's proceedings, and send a copy forthwith to the firm reported on.

18. That every member have free access to the results recorded in the office of the secretary; but in all books and reports open to the inspection of the members, each firm shall be designated by a number, and the names of firms shall only be given with their consent.

19. That, unless prohibited by the owners, the chief and sub-inspectors shall, at all reasonable times, have access to the steam boilers of the members, and to all apparatus connected therewith on which safety depends.

20. That it shall be the duty of the chief inspector to give to the members every information and all useful facts which his experience and knowledge of results supply in respect to the various forms and construction of steam engines, boilers and furnaces, and all apparatus appertaining to them, so as to guide the members to the safest and most economical means of raising and using steam. But it is not intended that the inspectors, either in testing boilers or other apparatus, or in communicating information, or advising in respect to any matter or thing in the discharge of their duties, shall take upon themselves any responsibility to supersede in any degree that of the members or their servants.

21. That the responsibility of the committee be limited to the duty of selecting the most trusty and experienced officers they can find, or whose services they can obtain, and to provide for reference a faithful record of all important facts and results obtained in the course of inspection, such results to be given in a condensed and tabulated form in a yearly report of the proceedings to the general meeting.

22. That parties residing at a distance out of the sphere of the operations of the association be admitted corresponding members, and be entitled to copies of all the reports and statements printed, and have access to all the documents prepared for reference by the members within the circuit, on payment of a yearly subscription of £2.

APPENDIX V.

Report by William Fairbairn, *Civil-Engineer, Manchester;* James Leslie, *Civil-Engineer, Edinburgh; and* Robert Johnston, *Brick-Builder, Glasgow; to the Dean of Guild Court of Glasgow.*

My Lord and Gentlemen,

In pursuance of your remit to us of date the second day of March last, in the action depending before you, at the instance of the Procurator Fiscal of Court, Pursuer, against Messrs. Charles Todd and Higginbotham, Defenders, we have visited and carefully inspected the Defenders' premises in Commercial Road, Hutchesontown of Glasgow, and investigated and considered the whole matter remitted to us, and have now to report to you the result of our deliberations. This we propose to do by describing (1st), the state of the Defenders' premises, with reference to the subject of our investigation as we found them on examination; and (2nd), the remedies and directions we have to suggest for removing or abating the nuisance of smoke, complained of as arising from the Defenders' Works.

I.—*State of Premises.*

The Cotton Manufactory, of which the Defenders are the occupiers, is situated in Commercial Road, Hutchesontown, in the town of Glasgow. It contains 500 power-looms, and is worked by a condensing steam engine of 25 nominal horse power. The cylinder is 28¼ inches diameter, 5 feet stroke, and makes 36 strokes per minute. It is supplied with steam from four boilers and four furnaces of the following dimensions, namely:—

	Boilers.				Furnaces.					
	Length.		Diameter.		Length.			Breadth.		
	ft.	in.	ft.	in.	ft.	in.		ft.	in.	
No. 1.	16	0	7	0	4	6	×	4	0	
No. 2.	19	0	6	0	6	0	×	4	6	
No. 3.	16	0	5	0	4	0	×	3	6	
No. 4.	20	0	6	0	5	0	×	4	6	

All these boilers are of the same (cylindrical) construction, with flat ends, with the exception of No. 2, which has a centre flue.

The furnaces are placed immediately under the boilers, as shown in a sketch which we submitted (No. 1), and the flame travels the length of the boilers three times along the bottom and two side flues, before it enters the chimney.

By this arrangement, the heated currents or carbonaceous matter passes from the furnace along the bottom to the extreme end of the boiler, where it ascends into the side flue A; it is then conducted along the side and across the flat end in front into the flue B, whence it escapes into the chimney.

By this process it will be observed that the gaseous products of the furnace make a circuit of three lengths of the boiler before they finally arrive at the main flue that conducts to the chimney.

Three of the boilers, Nos. 1, 3, and 4, are built or placed in this manner; but No. 2 having a centre flue requires a different construction. In this boiler the flame passes, as before, along the bottom; it then rises into the centre flue, and arriving at the front end separates into two distinct columns, and thence passes onwards to the chimney. This boiler, from its enlarged heating surface, is a superior generator of steam to those constructed without internal flues, but defective when compared with others of more modern construction. The whole four boilers are in use for raising steam to supply the engine, excepting only a small portion, probably about one-sixth, which is taken to boil and prepare size for the looms.

The consumption of fuel, when compared with the power of the engine, is very considerable; and contrasting it with other establishments, it appears that nearly one-half is wasted, passing either into the ash-pit or the atmosphere unconsumed.

In attempting to estimate the quantity of coal used by this engine, unfortunately we have no indicator diagrams to guide us, either as regards the vacuum or its general working condition. But assuming the velocity of the piston to be 360 feet per minute, and the pressure of steam 15 lbs. on the square inch, a force of not less than 75 horse would be the result. The horse-power in this case is taken at 33,000 lbs., raised one foot high in a minute.

Comparing this with the quantity of coal consumed, 40 tons per week, we find the enormous expenditure of 19¾ lbs. of coal per horse-power per hour, and that calculated at 75 horse, the assumed power given out by the engine.

In a well-constructed condensing engine of this kind, the consumption of coal should not exceed 10 lbs. per horse-power per hour, including that used for boiling, preparing size, and heating the mill.

In our best-constructed engines working expansively, the consumption does not exceed 4 lbs. per horse-power per hour, and when carefully and well-managed, is reduced as low as 3½ to 3¼ lbs.

We have stated these facts to show how great and unnecessary a waste is going on in this comparatively small establishment, and probably in

many others of the same description in the city of Glasgow. A wasteful expenditure of this kind is invariably accompanied by its attendant evil, smoke.

Taking into consideration the heavy load the steam-engine has had to overcome, and the defective state of the boilers, we were not surprised at the quantity of fuel consumed, and the annoyance these works must have caused to the neighbourhood. It is our opinion that these defects *may be remedied*, and for this purpose we respectfully submit the following suggestions and directions:—

II.—*Remedies and Directions.*

There are innumerable schemes and patents at present in operation for the consumption of smoke;—Moving Grate Bars, Juke's Patent, Witty's Universal Smoke Consuming Apparatus, and a hundred others. Wishing, however, to avoid all complexity and unnecessary expense in construction, we are of opinion that the object may be effected in one of three ways; namely, 1st, by a common circular boiler of sufficient power; 2nd, by the introduction of the double flue and double furnace boiler, with alternate firings, which is probably a more economical plan than the preceding; or, 3rd, by the introduction of one of the multitubular boilers, 24 feet long, 7 feet diameter, with double furnaces, mixing chamber, and about 110 to 120 3-inch tubes (as shown in sketch which we submitted, No. 2), which is the best and most approved plan.

In the above construction of boiler, A is the furnace shown double at B, B, in the section; C is the mixing chamber where the gases passing from both flues are united; *a*, *a* are vertical tubes, of which there are three of about 12 inches diameter, made conical, and intended as stays for that part where the two flues pass into one, forming an ellipse at one end and a circle at the other. These tubular stays not only strengthen and retain the ellipse in form, but they answer the double purpose of powerful generators, as the heated currents impinge against them in their passage from the furnace to the mixing chamber, and to the tubes D, where the remaining portion of the heat is absorbed.

With this description of boiler, assuming the engine to be in good working condition, and that proper attention is paid to the management of the furnace, the emission of great volumes of smoke may be greatly mitigated, if not entirely prevented, and that by a few simple rules very easy of application. These rules will be found at the end of the report.

Boilers thus constructed, are calculated, from the large absorbing surfaces which they contain, to be excellent generators of steam. They require no brick flues, and one boiler of this kind will raise as much, if

not more steam, than the whole four put together, and now at work at the Defenders' mill.

We may also state, that we consider that two boilers of this description would effect a still greater saving by adopting the system of slow combustion as used in Cornwall, and by these means ensure not only the abatement of the nuisance, but a still further economy in the consumption of fuel; and further, that if the working parts of the Defenders' engines were strengthened to a force of resistance equal to 20 or 25 lbs. on the square inch, and the steam cut off at one-third of the stroke, the same power could be applied with an additional saving of one-half, if not three-fourths, of the fuel now consumed.

To abate the nuisance of smoke, and to effect a more general system of improvement in the process of working engines and raising steam, it is essential to use every means to prevent the escape of heat: that the recipient surface of the boiler should be of such extent as would absorb the whole of the heat as it passes from the furnace to the chimney, excepting only as much as may be required to maintain the draught: that the boiler thus constructed should be carefully covered with felt, or some other non-conducting substance, to prevent the radiation of heat: that the water for feeding should be raised to the boiling-point before it enters the boiler (and this may be done by enlarging the surface of the conducting feed-pipes, and surrounding them by the heated currents as they pass from the boiler to the chimney); and, finally, that the steam pipes, cylinder, and all those parts communicating with the boiler to the condenser, be carefully clothed in the same way as the boiler itself, and that every care be taken to retain the heat and prevent its escape.

These precautions being taken, we beg now to refer to the Rules for the proper management of the furnaces of steam boilers, which we have reason to believe, if properly applied, will prove beneficial to the proprietors of works, and acceptable to the public.

We would further respectfully submit the following remarks and suggestions relative to the management necessary to be generally observed in working the furnace, and the principle upon which that duty should be effected, and which we have added to our Report by way of Appendix:—

General Remarks given as an Appendix with the foregoing Report.

The steam-engine, taken as a machine, has much to do with the economy of fuel, either as regards the amount of force applied, or the savings to be effected in the consumption of coal.

The steam-engine, as left by Mr. Watt, was a perfect machine, as far

as regards the principle on which its erection was founded, and in this respect it has undergone no change. It has, however, been greatly improved in its parts, and by the introduction of malleable iron, improved tools, and increased strength in its organic construction, we are now enabled to apply steam of great force, and that, united to the principle of condensation and expansive action, has rendered the steam-engine an agent of motive power that may be carried to almost an unlimited extent. In fact, the measure of its force is alone calculated by the security of its application; and as that security almost entirely depends upon the boiler, that important adjunct requires our special attention both as regards management and construction.

When the steam-engine was first constructed, 3 to $3\frac{1}{2}$ lbs. pressure upon the square inch was all that could be ventured upon; progressively it got up to 7, 8, and 10 lbs., and now the last and most economical are worked at 30 lbs. on the square inch. In locomotive and non-condensing engines, steam is worked with perfect safety at a pressure varying from 50 to 150 lbs.

In Cornwall, where fuel is more expensive than at Glasgow, and most other places, even where coal is abundant, it becomes a question of deep importance to the different mining companies that the greatest economy should be observed in the combustion of coal; and such is the feeling on this subject, that the captain of the mines no sooner observes smoke issuing from the chimney, than he at once accuses the engineer of *wasting coal*, and unless the outlet of the chimney is immediately rendered transparent, a reprimand or probably a small fine, with the disgrace of mismanagement, is the result.

Slow combustion is in most cases preferred in Cornwall, and it frequently happens, that the furnace when charged in the morning is not again touched till noon, when the fire is cleaned and recharged with quantities sufficient to last the same time as before. In this way the fire is never disturbed for several consecutive hours, and on looking into the furnace there is a slow smouldering fire which consumes every particle of coal, and maintains the full pressure of steam up to 30 and 40 lbs. on the square inch. To fire in this manner, and to maintain the steam at the required pressure, two essentials are requisite, namely, *plenty of boiler surface and warm clothing to prevent the escape of heat.* In other parts of Cornwall the system of slow combustion is not carried to the same extent, as many of them fire their furnaces once an hour, but with the same success as regards the emission of smoke; and it is no uncommon occurrence to witness a dozen chimneys of great power and dimensions, carefully whitewashed, with an atmosphere above them as clear and transparent as if the fires below did not exist.

Such is the practice in Cornwall; and if this can be done by good management and careful attention in that district, why is it not accomplished in others equally well prepared for its reception? This question naturally suggests itself to every person who witnesses the repulsive dark atmosphere which hovers over the seats of our manufactures.

Cornwall, from the almost total absence of smoke, is a leading example to most other parts of the kingdom where steam-engines are employed, and extensive works carried on; it would, however, be unjust to say that attempts have not been made to remedy the evil of smoky chimneys, so justly complained of in other counties; on the contrary, we believe that great efforts have been made in various directions to remedy the evil: but, looking at the nature of the works, and the many fruitless attempts to accomplish a great deal in a small space; and, judging from experience, we are led to the conclusion that all attempts at a radical cure will be unavailing, so long as a determination exists to *work steam-engines with boilers of limited capacity.* Our attempts have been hitherto to save fuel, and effect perfect combustion under boilers of capacity insufficient to raise and maintain the required pressure of steam without forcing the fire. Now, it should be distinctly understood, that it is next to impossible to burn smoke, or effect perfect combustion, when the fires have to be forced. We might as soon expect to work a factory, or propel a steam-ship, at high velocities, by the wind, as supply an engine from a boiler of limited dimensions without producing smoke.

In fact, the whole secret of economy in combustion, and the absence of smoke, is plenty of boiler space, and that consideration should never be lost sight of in our attempts at improvements in that direction.

Numerous attempts have been made to abate the nuisance of smoke by the admission of air through the fire doors, under the bars, and behind the bridge. These have been more or less successful as the boilers have been of enlarged or limited capacity. Nothing has, however, been done to justify an adhesion to any particular plan; nor has any particular project attained such a preference in public estimation as to induce its general application.

Mr. C. Wye Williams has laboured incessantly, and in some cases successfully, to remedy the evil; and on board of some of the City of Dublin Steam Navigation Company's vessels, he has proved by experiment and continued practice, that even on board ship, where the boiler space is necessarily limited, much can be done to abate the nuisance, and that with a considerable saving of fuel.

It is stated as the result of considerable experience, "that it was a matter of perfect indifference in what part of a furnace or flue the air was introduced provided this all-important condition was attended to and

satisfied; namely, the effecting the mixture of the air and the gas before the temperature of the latter was reduced below that of accension or kindling. This, according to Sir Humphry Davy, should not be under 800° Fahrenheit, as ignition could not take place at a lower temperature, that fact being the principle of safety in the miner's lamp.

"Previously to the introduction of the tubular in place of the flue system in marine boilers, it had been supposed that the introduction of the air on the argand principle by a perforated plate behind the bridge, satisfied all that nature required in producing perfect combustion. The tubular form of boiler, however, rendered a different arrangement absolutely necessary. This was occasioned by the run or distance between the bridge and the tubes being so very short, and consequently the passing along that distance being so limited in time, that the mixing and combustion could not be adequately affected. This, after numerous trials and expedients, led to placing the orifices of admission in the front or at the door-way end of the furnace. The system adopted by boiler-makers of contracting the door-ways of marine boilers, much impeded a successful application of the argand principle. The enlarging the door-way opening, as shown in the models, however, afforded sufficient space for the required number of $\frac{3}{4}$ or $\frac{1}{2}$ inch orifices. By this the length of the furnace from the door to the bridge was thus, as it were, added to the length of the run. By this mode of construction, the argand principle had been applied with great success to marine boilers.

"The next point considered was as to the quantity or gross volume of air required, and the area of aperture necessary for its introduction. On this head it was stated, that a great practical error had been frequently committed, as it had been stated, that it would suffice if the aperture should be equal to $1\frac{1}{2}$ square inch for each square foot of fire surface in the furnace, in the case of single furnaces; and of but half a square inch or 0·5 inch for each square foot of grate-bar surface in the case of double-furnaced boilers."

Mr. Williams further states, in reference to a skilful fireman, that the only duty that should be required from him, is, "that he should keep the grate bars fully and uniformly covered, for if the back end or sides of a furnace were left uncovered, the air would pass through them instead of passing through the air distributors, as that passage offered the hottest and shortest route to the chimney." In this opinion we perfectly concur, as unless the bars are covered, it is sure to cool down the temperature and occasion great waste of fuel.

In a private communication with one of the reporters, Mr. Williams contends for the use of his air-diffusion plates behind the bridge on the principle of the argand burner; but there is this difficulty, that the very

evil we are anxious to avoid, is to some degree aggravated by an excess of air, or as he himself calls it, "an overflooding," which should be carefully avoided if we are to economise fuel by the same process that we get rid of the smoke. Mr. Williams very properly observes, that we must keep in view that the gas of a ton of coal requires,

in cubic feet	100,000
and the solid part, or carbon	200,000
A total of . .	300,000

cubic feet of hydrogen and oxygen for the combustion of one ton of coal. These are facts which have been determined by Mr. Williams experimentally, and the public are greatly indebted to that gentleman for the able manner in which he treats his subject, and the great amount of intelligence which he has brought to bear upon the principle as well as practice of obtaining a better system of management, and in following up a more correct principle of combustion.

From Mr. Williams' statement given above, and from the various projects adopted by others for the attainment of the same objects, it appears to be the general opinion that the admission and diffusion of air behind, or through the bridge (marine boilers only excepted), is the only feasible means of preventing the generation or emission of smoke. This is certainly an effectual remedy as far as it goes, but injurious as regards the economy of fuel, and that for the following reasons:—namely, that an aperture for the admission of an increased quantity of oxygen required to assist combustion after the furnace is charged, is not wanted, when the coal has been deprived of its bitumen; after that period, when the furnace becomes bright, a smaller quantity is required, and any excess beyond what is necessary to combine with the gases accelerates combustion, cools down the furnace, and increases the quantity of fuel consumed. Now, in situations where the boilers are in excess of the power, these apertures are *not* required, as the Cornish system of slow combustion clearly demonstrates, whilst, at the same time, it teaches how that process may be adopted, and that with the same success as exists in that district. At other times where the boiler space is limited, the introduction of the air diffusion principle will greatly mitigate the evil, but it will not, in our opinion, effect the same satisfactory remedy as may be obtained by enlarging the power of the boilers.

In cases where the owners of furnaces have to force the fires, and are limited beyond the power of enlarging their boilers, we should then recommend for adoption the multitubular system, which affects in a small space what would otherwise be required by increasing the number of, or dimensions of, those of the common construction. This tubular

system is always effective, provided sufficient surface is given to absorb the heat as it passes from the furnace. In marine and stationary boilers 16 to 18 square feet has been considered sufficient for every *nominal* horse-power of the engine, but it is safer and better to take 24 square feet, provided a saving of fuel, accompanied by the absence of smoke, is to be effected. With that measure of heating surface much may be done; but it will be found still far from perfect, unless care and constant attention be paid to the management of the furnace.

In this respect a good system of management becomes indispensable, and although firing machines have been adopted, with numerous ingenious devices for regulating the time of firing, and other projects for accomplishing the same object by the diminution and pressure of the steam, yet we have never found these self-acting machines answer the purpose so well as the human hand. The management of the furnace appears to be a separate system, which may be learned by attention to a few simple rules, so as to give perfect satisfaction.

In these statements we have endeavoured to lay before the authorities such information as appears to us calculated to abate the nuisance of smoke, and purify the black dense atmosphere which hangs over the city of Glasgow. That these dark and gloomy vapours can be prevented from ascending, we entertain no doubts; and after the observations we have considered it our duty to make, and which apply with equal force to other manufacturing towns, it rests with the public authorities of the city to enforce, mitigate, or improve these practical recommendations.

W. FAIRBAIRN.
JAMES LESLIE.
ROBERT JOHNSTON.

In the Dean of Guild Court of Glasgow.

Further Report by WILLIAM FAIRBAIRN, JAMES LESLIE *and* ROBERT JOHNSTON, *in the Case at the instance of the Procurator Fiscal of Court against* Messrs. CHARLES TODD *and* HIGGINBOTHAM.

MY LORD AND GENTLEMEN,—In obedience to the further remit of Court of date the fifth day of October last, we have again visited and carefully inspected the Defenders' premises, and have now to report, that we have seen no cause to alter in any respect our former report, which we therefore adhere to and confirm. In that report we described accurately the state of the Defenders' Works as we found them, showing that a great and unnecessary waste of fuel was there going on, and that a wasteful expenditure of that kind was invariably accompanied by its attendant evil—smoke. We then pointed out how this state of things might be remedied, and the consumption of smoke effected. This object, we stated, might be attained in one of three ways, namely:—(1) by a common circular boiler of sufficient power; (2) by the introduction of the double flue and double furnace boiler with alternate firings, which, we stated, was probably a more economical plan than the preceding; or (3), by the introduction of one of the multitubular boilers 24 feet long, 7 feet diameter, with double furnaces, mixing chamber, and about 110 to 120 three-inch tubes, as shown on a sketch which we submitted (No. 2); this we distinctly added, being in our opinion the best and most approved plan. In addition to this, we gave rules to be observed in the management of the furnace. Remaining of the same opinion, after inspection and deliberation, we cannot suggest any other remedies.

We observed, on our second visit, that the Defenders had, to some extent, complied with the instructions in our former report, and thereby effected a considerable improvement; but there is yet much to be done to lessen the emission of smoke from their chimney; and we do not think, therefore, that their partial compliance with our instructions ought to be accepted, as satisfying the requirements of the statute referred to in the remit to us. At any rate, we hold it not to be in our province to recommend anything short of the best and most approved plan known at the time, as we have done; and that if any other plan is to be adopted, this must be matter of arrangement betwixt the parties, with which, we presume, we have no power to interfere.

All which is respectfully reported by

W. FAIRBAIRN.
JAMES LESLIE.
ROBERT JOHNSTON.

1st March, 1855.

APPENDIX VI.

Experiments on the Iron Targets at the Arsenal, Woolwich.

The following experiments were undertaken to determine the effect of shot upon the hull of an iron vessel, and also with the view of providing means for stopping the passage of water through a shot-hole near the water-line. The latter object is sought to be effected by packings of various kinds fixed behind the sheathing plates, and which by their elasticity will close over the hole after the passage of the shot through them.

The gun used in the experiments was a 32-pounder, placed at the distance of thirty yards from the targets, and loaded both with the full charge of 10 lbs. of powder, and a charge of 2 lbs., to produce the effect of a long shot. The initial velocity of the ball with the full charge is about 1800 feet per second, and of the 2 lbs. charge 1000 feet. The diameter of the shot is 6 inches.

Target No. 1. is made of three thicknesses of $\frac{1}{2}$-inch plates, riveted together by double rows of rivets, arranged in rectangles of 24 in. × 14 in. Through this only one shot was fired with the full charge, which made a clean hole, with very little tearing or raising of the edges, and no rivet heads started near the hole. The three thicknesses cut out by the shot all flew into angular splinters of 1, 2, and 3 inches long, diverging from the hole in all directions. When the full charge is used, no disturbance in the plate or the rivets round the hole is observable. This target was not stiffened with angle-irons.

No lining was placed behind this target.

Target No. 2. is formed of single $\frac{1}{2}$-inch plates, flush-jointed, single-riveted, with two frames 9 inches deep attached by double angle-irons 6 in. × 3 in. One half of this target is lined at the back with pure India-rubber, and the other half with a mixture of India-rubber and cork-dust, containing 25 per cent. of the latter by weight, 12 inches thick. These linings are held to the sheathing by 1-inch screw-bolts with square heads outside, and nuts with washers of $\frac{5}{16}$-inch plate 8 inches square inside, the plates (or washers) completely covering the elastic lining. The bolts are in the centre of each square, or 8 inches apart each way.

Through the India-rubber and cork-dust five shots were fired, all striking (as was intended) between the bolts. Two with 10 lb.-charge made clean perforations through the outer shell, and passed through the lining without shattering it much, but knocking off, each, four or five of the back plates with great violence, and the splinters from the per-

foration in the outer shell passing through the lining also. The elastic lining closed completely over the hole, so as to exclude water thoroughly. Several proportions of India-rubber to cork-dust have been tried, but this one is found to be the best. The three other shots fired through this lining were with the 2 lb.-charge, and were purposely made to strike within a circle of 12 inches diameter, so that the three holes joined; still the lining closed over the holes so as to exclude light and to prevent the passage of a thin walking-stick through it where most shattered, which was considered very satisfactory. Of course a great many of the back-plates, about eight, were torn off.

With the small charge of powder the sheathing plate suffers much more than with the full charge, the plate being considerably drawn into the hole, raising the edge inside, and stripping the rivet heads near it. A shot was fired with 1 lb. of powder, which produced the same effect in a greater degree. In all cases the ball carries with it a part of the plate torn from the hole, which increases in size with the strength of the charge.

During the last experiment a splinter from the target struck a sentinel on duty at about 200 yards' distance, passing entirely through the calf of his leg. The piece was about the size of a penny, and must have glanced from the target at a very obtuse angle to have struck the man who was stationed a little before the line of the target.

A weak shot was passed through the lining of solid India-rubber, which perfectly closed over the hole, excluding water or even air from passing, but causing a great dislocation of the plates at the back, a great number of which had flown off from the nuts breaking in consequence of the pressure thrown upon them by the tenacity of the India-rubber.

Target No. 3 is formed of double half-inch plates riveted together, and no frames. Half is lined with solid India-rubber, not yet experimented with, 8 inches thick, and held on by bolts and square washers as before.

One chief objection to India-rubber as a lining is its expense, costing about £5 per cubic foot. Also it would be difficult to *confine* it in a warm climate, as it will assume a kind of semi-fluid motion when acted on by its own gravity (like sealing-wax).

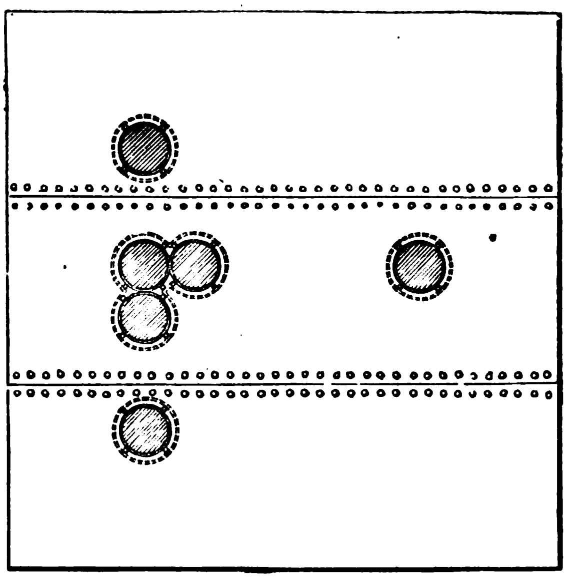
The other half of this target is lined with a mixture of India-rubber and cork-dust, 12 inches thick, held on as before. In this case the cork-dust was in too large a proportion to the India-rubber, and consequently the hole formed by the shot did not close to the same extent, and the lining itself was very much shattered.

Target No. 4 is formed by two thicknesses of half-inch plates with a space of $1\frac{1}{2}$ inch between them filled with flannel, flush jointed, single

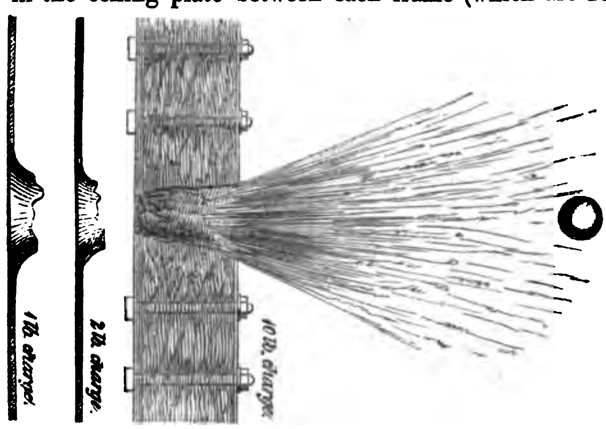
riveted, no frames. The rivets to hold the flannel are 6 inches square from each other. This has not yet been experimented with.

Target No. 5 is formed of two plates having a space of 10 inches between them, half of this space being filled in with felt, and half with

Target No. 2, 6 feet square.



India-rubber and cork-dust introduced in small pieces through hand-holes cut in the ceiling plate between each frame (which are 15 inches



apart). The outer sheathing plate is $\frac{5}{8}$ in. thick, and the ceiling $\frac{5}{16}$ in.

The felt proved of no use in stopping the hole, and by its pressure it tore away a large part of the ceiling plate, about 2 square feet, where

the ball passed through. This large piece was quite detached from the plate in various fragments, which seem to have broken off quite short.

A similar effect was produced in the ceiling plate by the passage of the shot through the lining of India-rubber and cork-dust, and the latter, from being introduced in small pieces, did not close over the hole, and was very much displaced.

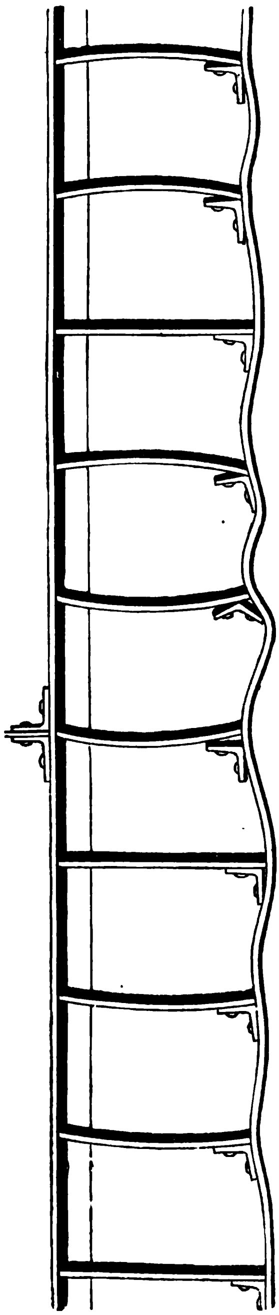
Some of the balls made from hot blast iron broke on Target No. 3. The velocity of the ball makes but little difference in the state of the lining after a shot.

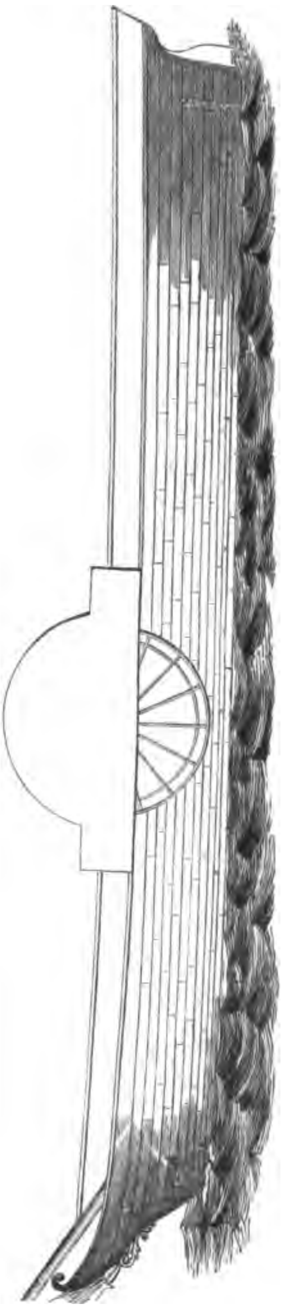
APPENDIX VI.*

Mr. Clark's letter descriptive of the injuries sustained by the 'Vanguard' referred to in Lecture VI.

DEAR SIR,—Agreeably to your instructions, I proceeded to passage to survey the 'Vanguard' steamer on the 3rd inst., and I herewith send you a rough sketch with a view of conveying a better idea of the position she was in while on the rocks as well as the injuries she has sustained: these could not be well done in letters without it.

Figure 1 is intended to represent the position of vessel when aground: her bottom appears as if it had rested on a number of hard small rocks, from the stem to the full part of the vessel just under the paddle-wheel; and from that part to the stern, I have no doubt, was quite unsupported except where the keel was broken at C, as shown at the stern at fig. 1 and fig. 4, which latter fig. represents the way the keel was bent up a little within the bulkhead B, which is 6 feet from the stern-post. I was informed, while the vessel was on the rocks, that she beat very hard, and there can be no doubt of it, for the bottom of the vessel entirely under both the engines and boilers show it. The plates on both sides of the keel (although half an inch in thickness) are bent upward between the floorings, and in some places the flooring is very much bent and the angle-iron is quite separated from them; however, notwithstanding the damage done to the bottom, there is only *one* hole in it produced by the rocks; and what is likewise very satisfactory, the entire derangement is confined to the hull and the floorings. Fig. 2 is a longitudinal section of the hull to the top of the keelsons, represented at D, and which are now as perfectly level at the top, the entire length of the vessel, as they were the first day, and so are all the bulkheads above the keelson, although bent, as shown in drawing, below them. E in fig. 2 represents the bulkheads above the keelson.





VANGUARD.

There is one thing I observe in the top sides at A in fig. 1, which, in reference to fig. 3, will be better understood. From the gunwale down to the blue lines all the joinings of the plates are what are commonly called "jump joints:" this is generally done to make smooth work; in nearly all the upright joints (particularly abaft the engines) they have now the appearance as marked in fig. 3, viz. being wider at the bottom of the joints than at the top, which in my opinion has been produced by beating on the rocks, and particularly from her having no support under that part of the vessel. Lap-joints would be much stronger, and I have no doubt the builders thought so; as all the joints on the bottom under the engines and boilers are lap-joints.

In my opinion, there is not a stronger instance on record that has afforded more convincing proofs of the superiority of iron over wood than this vessel; and although she was beating hard for so many days, no part of her engines was deranged. Her engines were kept constantly at work, and in my opinion are now in as permanent working order as they ever were. Had the 'Vanguard' been built of wood instead of iron, she could not have been saved.

Your obedient Servant,

(Signed) Joseph Clark.

Note referring to Lecture V.

In Lecture V., "On the Necessity of incorporating with the Practice of the Mechanical and Industrial Arts a Knowledge of Practical Science," I endeavoured to show how neglectful the Government of this country is, in comparison to that of others, in giving its support and encouragement to science and its contributors.

That subject is now under the consideration of the British Association fer the Advancement of Science, and in reference to those deficiencies on the part of the Government, as pointed out in the lecture, I have the satisfaction to submit for consideration the impressions of the Committee, as contained in the annexed letter, addressed by Lord Wrottesley to Lord Aberdeen, at that time at the head of Her Majesty's Government.

The British Association, ever alive to the interests of science, has long had it in contemplation to recommend to the Government of this country the adoption of measures calculated to extend science, and to improve the condition of those men who have devoted their lives to its cultivation.

For these objects a Parliamentary Committee was appointed, headed by the President of the Royal Society; and after the discussion which

ensued on the replies received by the Committee from the most eminent cultivators of science, the Committee, at their first meeting, proposed the following queries :—

1st. How can the knowledge of scientific truths be most conveniently and effectually extended ?

2nd. What inducements should be held out to students to acquire that knowledge; and, after the period of pupilage has expired, to extend it and turn it to useful account ?

3rd. What arrangements can be made to give the whole body of competent men of science a due influence over the determination of practical questions, dependent for their correct solution on an accurate knowledge of scientific principles ?

The Committee, for the purposes of inquiry, divided each of the three questions into two; namely, with reference to those who resort to the universities for education, and to those who do not. On the first of these questions, the Committee refer to their report of the meeting at Liverpool last year.

In that report it is stated, in a letter from the President of the Royal Society, Lord Wrottesley, to Lord Aberdeen, that—

"As Chairman of the Parliamentary Committee of the British Association appointed for watching over the interests of science, I have been requested to address you on a subject of great importance to those interests.

"Your Lordship is probably not aware, that soon after the accession of the late Government to power, Sir Robert Inglis and myself solicited and obtained an interview with Lord Derby, in which we represented to him that considerable dissatisfaction prevailed among the cultivators of science generally at the bad success which had attended certain then recent applications for pensions to some eminent scientific individuals, which had been preferred by the President of the Royal Society; and by subsequent investigations it was ascertained (and I communicated the fact to Lord Derby, by letter dated April 1852) that since the accession of Her Majesty, about thirteen per cent. only of the annual sum allowed by Parliament to be granted for pensions to deserving persons had fallen to the lot of science, a result which naturally contributed to increase that feeling of dissatisfaction to which I have already adverted.

"It appears that a recent application by Lord Rosse of a similar character has been unsuccessful, and that your Lordship, in declining to accede to it, expressed yourself as follows :—'In order to meet even a small portion of the claims preferred to me, I have been compelled to require that poverty should be the attendant of merit, and that the pension should be as much the relief of pecuniary distress as the acknow-

ledgment of intellectual attainments.' Lord Rosse could not, of course, consider a letter from your Lordship on a subject of vital importance to science in the character of a private communication; and as that subject had already been referred to the consideration of our Committee, of which he is an influential member, a copy of your Lordship's letter was laid before it.

"Now, whatever our individual opinions may be on the merits of the particular case to which I have alluded, I purposely abstain from stating them, in order that the object of the present address may not be misunderstood,—that object being to represent to your Lordship, with all that respect which is justly due both to yourself, and to the high station which you occupy, that the views above expressed as to the disposal of the pension fund, would render absolutely nugatory, so far as science and its cultivators are concerned, all the benevolent intentions which Parliament and the country must be supposed to have entertained in their favour, when the provision in question was created.

"That the grant of a pension would be an inappropriate method of recompensing scientific merit when possessed by those who may be properly termed *rich*, I am disposed to deny; but if it were hereafter to be understood that the receipt of a pension from the Crown were full as much the indication of absolute poverty, as an acknowledgment of high intellectual attainment, we apprehend that the object of the grant would be hereafter but ill attained.

"Had such a view of the intention of Parliament been formally announced, the honoured names of Airy and of Owen, of Hamilton and Adams would never have appeared on the pension list; and that small encouragement to abstract science which has hitherto been dispensed by the British Government would virtually have been withdrawn; the bounty of Parliament and the Crown would have been looked upon in the light of alms, and men of eminence would not have consented to be paraded before the public as its needy recipients. Considering your Lordship's known appreciation of the claims of literature, and we hope we may also add of science, upon a nation which depends so essentially for its prosperity and even safety upon the progress of improvement in every branch of intellectual exertion, I cannot but express on my own part, and on that of my colleagues, our earnest hope that your Lordship will reconsider your views of the object of pensions, and refrain from exacting conditions for their enjoyment which cannot be otherwise than painful to all who have a high sense of the dignity of their pursuits, and may possibly be considered as tending to degrade it.

"I remain, &c.,

"WROTTESLEY."

Note referring to the Lectures on Steam and High-pressure Boilers.

The following useful Circular, addressed by the Lords Commissioners of the Admiralty to the Commanders-in-Chief, Captains, Commanders, &c. of Her Majesty's Navy, is so exceedingly appropriate and so much to the purpose, in regard to the management of high-pressure steam boilers, that I cheerfully transcribe it for the use of those to whom the management of these vessels is entrusted.

On the Care and Management of High-pressure Tubular Marine Boilers.

Several ships and vessels having been recently fitted with high-pressure tubular boilers, and no experience having yet been obtained in the working of such boilers with salt water, their Lordships desire all officers, under whose command these vessels may be placed, to impress on the engineers the necessity of paying more than ordinary attention to the boilers under their charge, both in maintaining the proper heights of water, and, by adequate blowing off, in keeping the degree of saltness below that which in low-pressure boilers would be no serious injury.

Even when full speed is required, these matters must be regarded as of paramount importance; for any neglect may cause an amount of permanent injury to the boilers, which would far outweigh the temporary advantages of a slight additional speed; and, until some experience has been obtained in the practical working of them, the most careful and frequent attention is required to ascertain with accuracy the degrees of saltness which the water has acquired, and which, at its utmost, should not exceed twice that of sea-water. When, however, the vessel is stopped, or is working at reduced speed, the opportunity should not be neglected to change the water in the boilers by increased blowing off, and by an ample supply of feed-water; and thereby to reduce its saltness *as much as possible*

Such precautions as these, as well as never opening the safety-valves suddenly to their full extent, or, at starting, admitting the full quantity of steam to the engines, will always be necessary to keep a high-pressure tubular boiler in a proper state of preservation and in effective working order; but they are more especially necessary before experience has shown the exact practices which may safely be adopted; and, until such

experience be obtained, the question of saving fuel, and all other considerations, must be regarded as of secondary importance.

The constant attention which will be required from the engineers in charge of the machinery of these vessels, and other circumstances, will, probably, at times, impose on them an unusual amount of labour and responsibility; but, as many of the boilers are precisely similar, the effect of judicious and careful management will be evident after a short time; and their Lordships will not fail to mark with their approbation those officers who have best performed their duty.

By command of their Lordships,

R. Osborne.

To all Commanders-in-Chief, Captains, Commanders, and Commanding Officers of Her Majesty's Ships and Vessels.

THE END.

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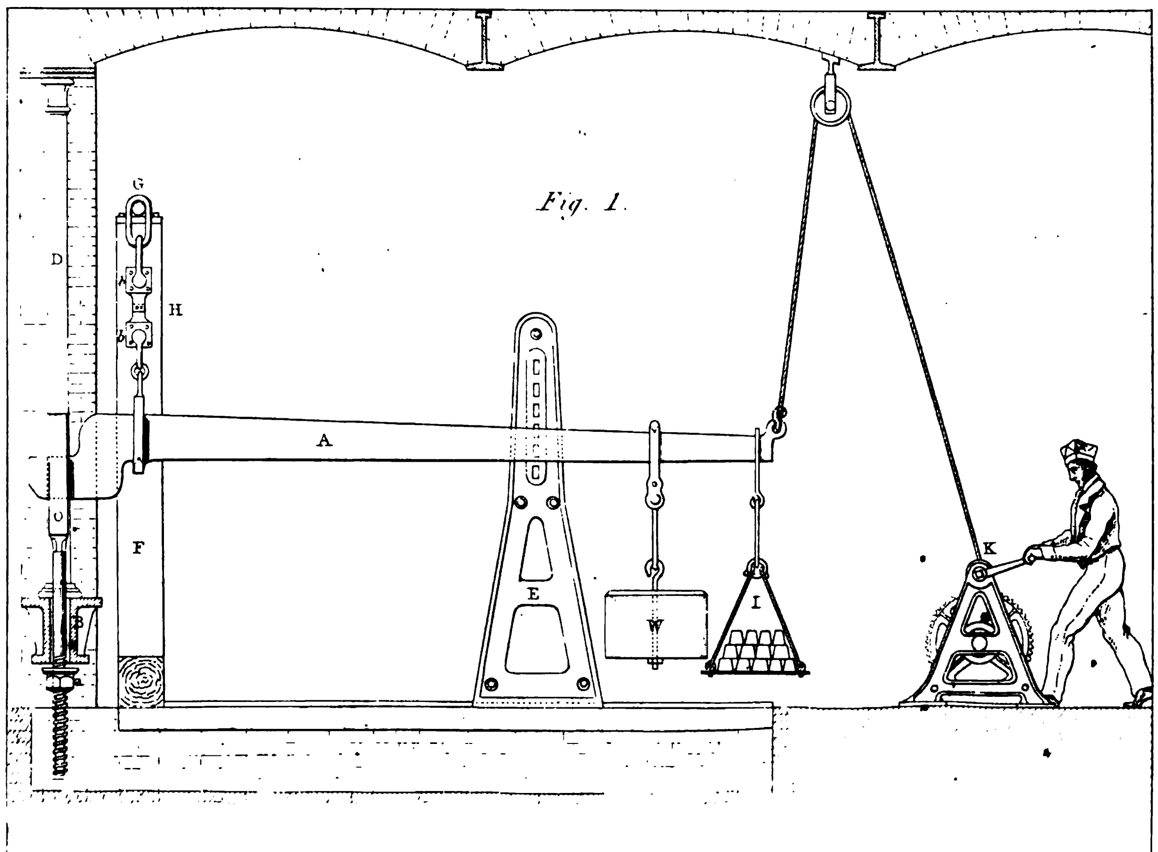
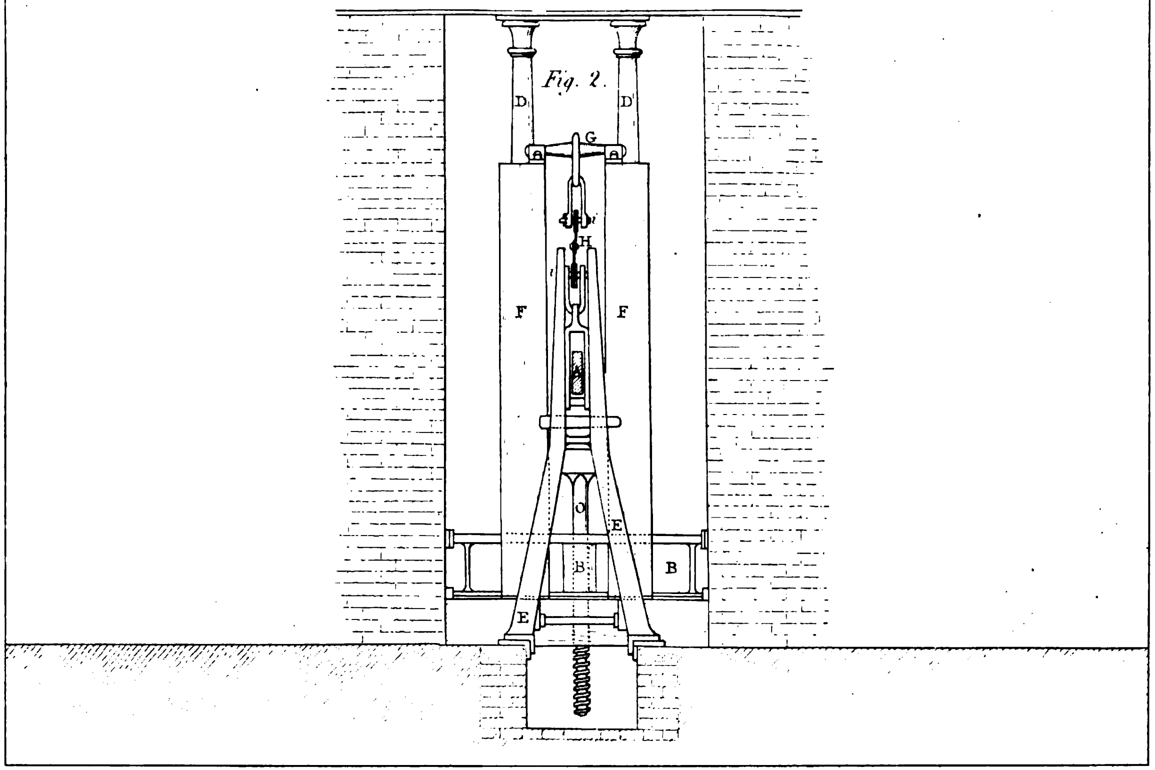
RED LION COURT, FLEET STREET.

Side View.



End View.

Fig. 2.



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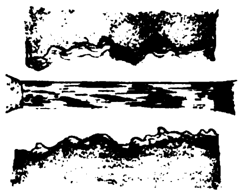
J. Basire sc.

YORKSHIRE PLATES.

TABLE I.



Drawn in the direction of the fibre

Breaking weight
in tons pr sq. inch 25.77
do do do 22.76
Mean do do 24.27

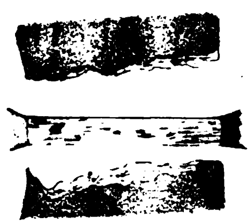
TABLE II.

Drawn across the fibre

Breaking weight
in tons pr sq. inch 27.49
do do do 26.03
Mean do do 26.76

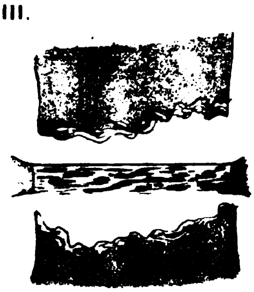
DERBYSHIRE PLATES.

TABLE III.



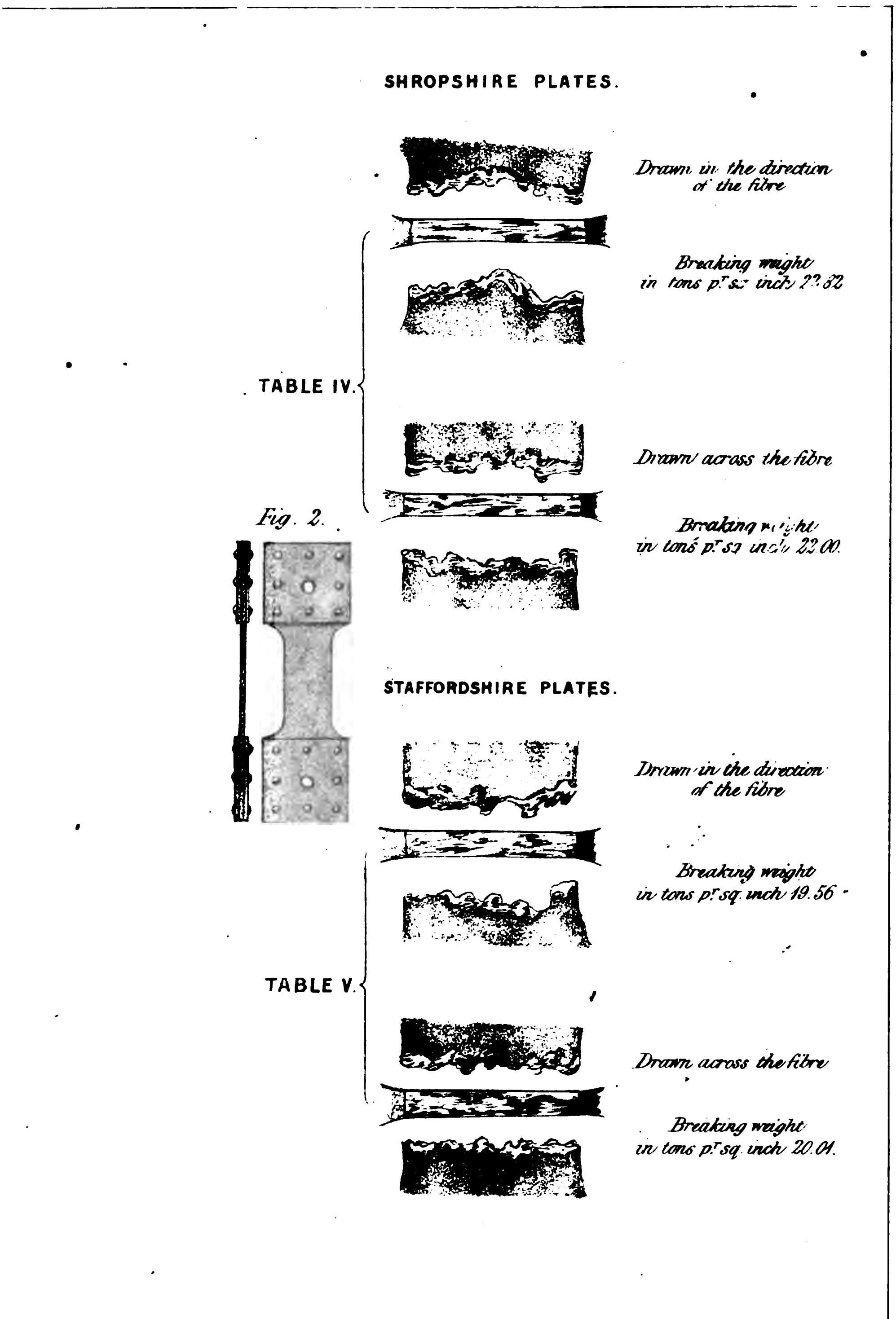
Drawn in the direction of the fibre

Breaking weight
in tons pr sq inch 21.65



Drawn across the fibre

Breaking weight
in tons pr sq. inch 18.65



J. Basire, Lith

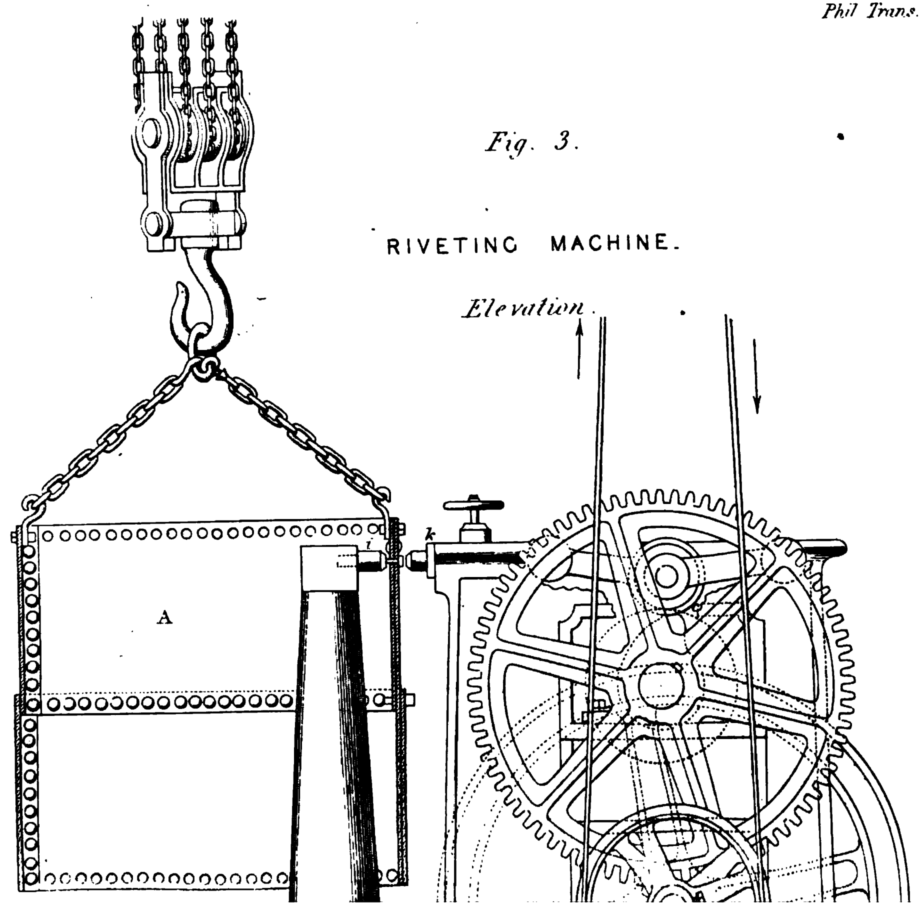
PLATE III.

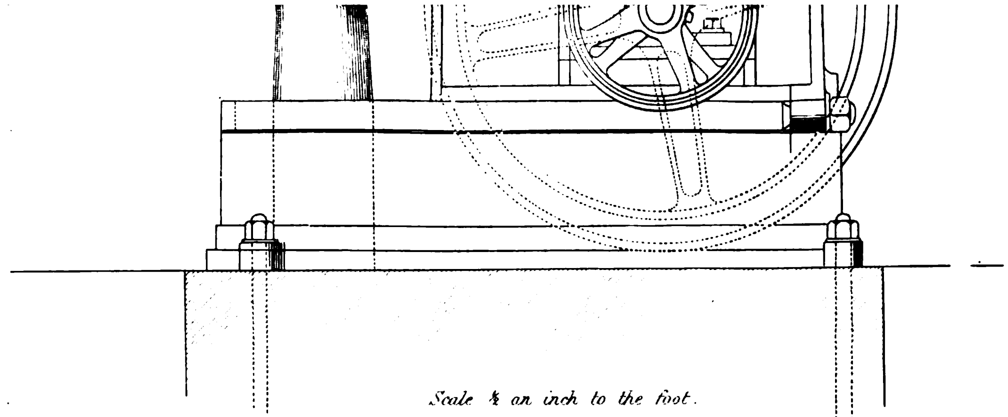
Phil Trans. MDCCCL. Plate LVI. p. 680.

Fig. 3.

RIVETING MACHINE.

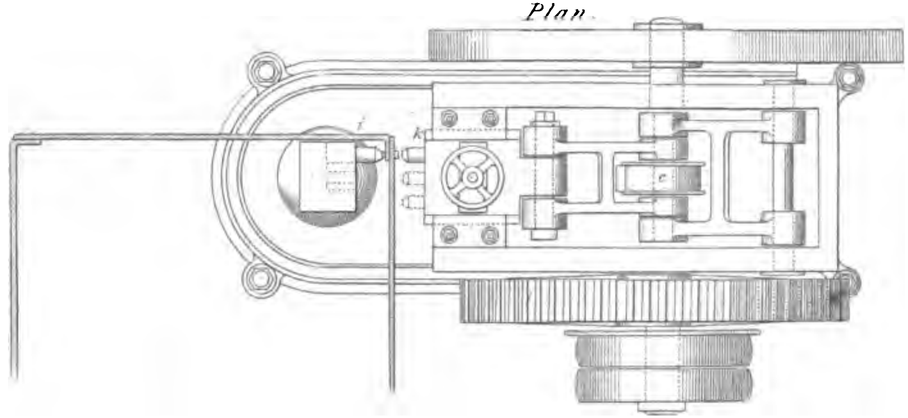
Elevation.





Scale ½ an inch to the foot.

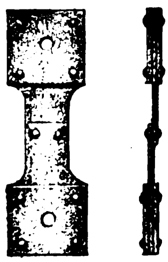
Plan.



J. Basire sc.

TABLE VI.

Fig. 4.



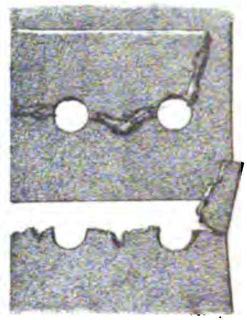


TABLE VIII.

Fig. 7.

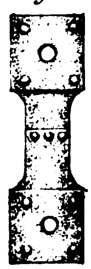
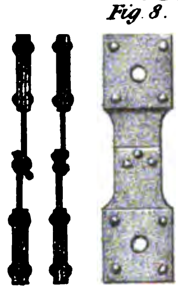


Fig. 8.



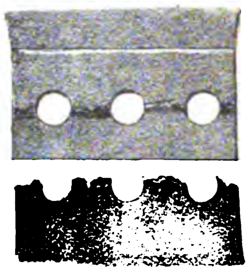


TABLE X.

Fig. 10

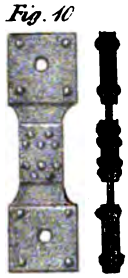
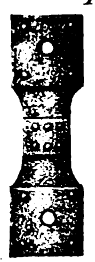


Fig. 11



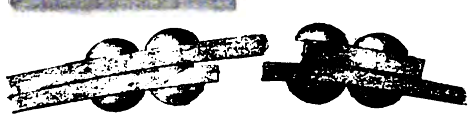


TABLE VII.

Fig. 5. *Fig. 6.*

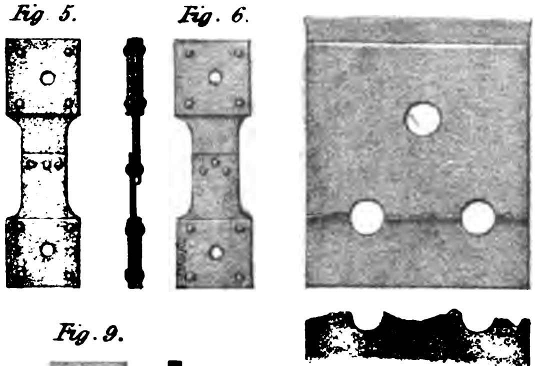


Fig. 9.

TABLE IX.

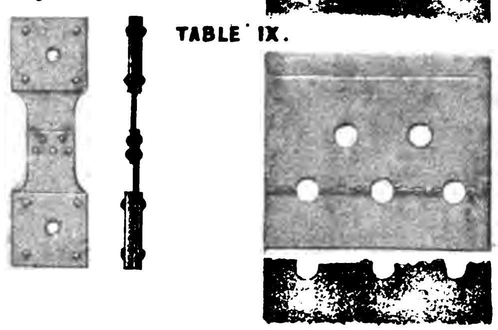
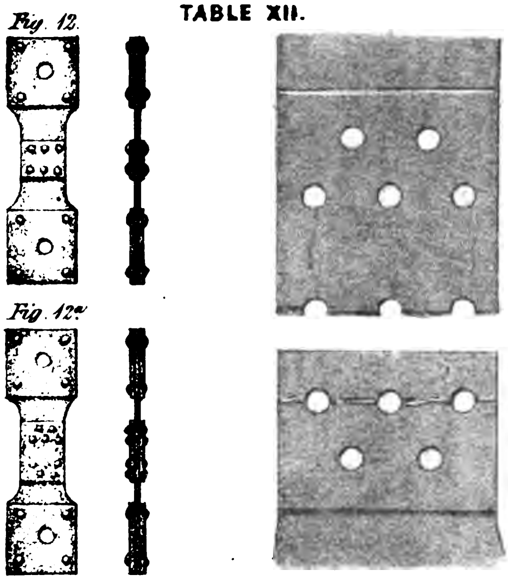


TABLE XII.

Fig. 12.

Fig. 12a



J. Basire, Lith.

TAB
Fig.

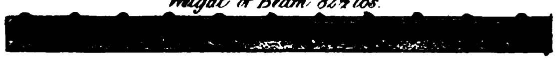
Beam before the Experiment rib downwards
Weight of Beam 54 lbs.

Beam after the Experiment

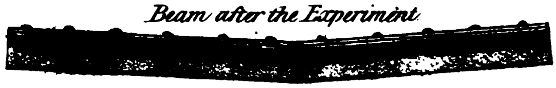
Beam, shewing the flange rib downwards.

TABL
Fig

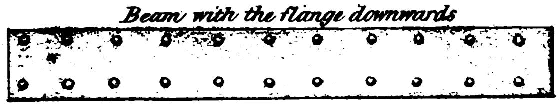
Beam before the Experiment rib downwards
Weight of Beam 82½ lbs.



Beam after the Experiment

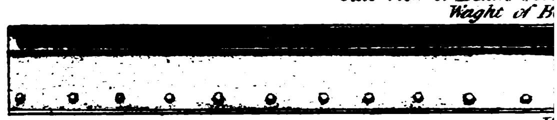


Beam with the flange downwards

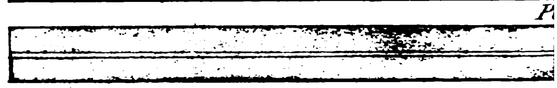


TABL
Fig
Side view of Beam bef
Weight of B

Section

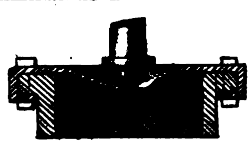


P



TABLI

Fig. 13.

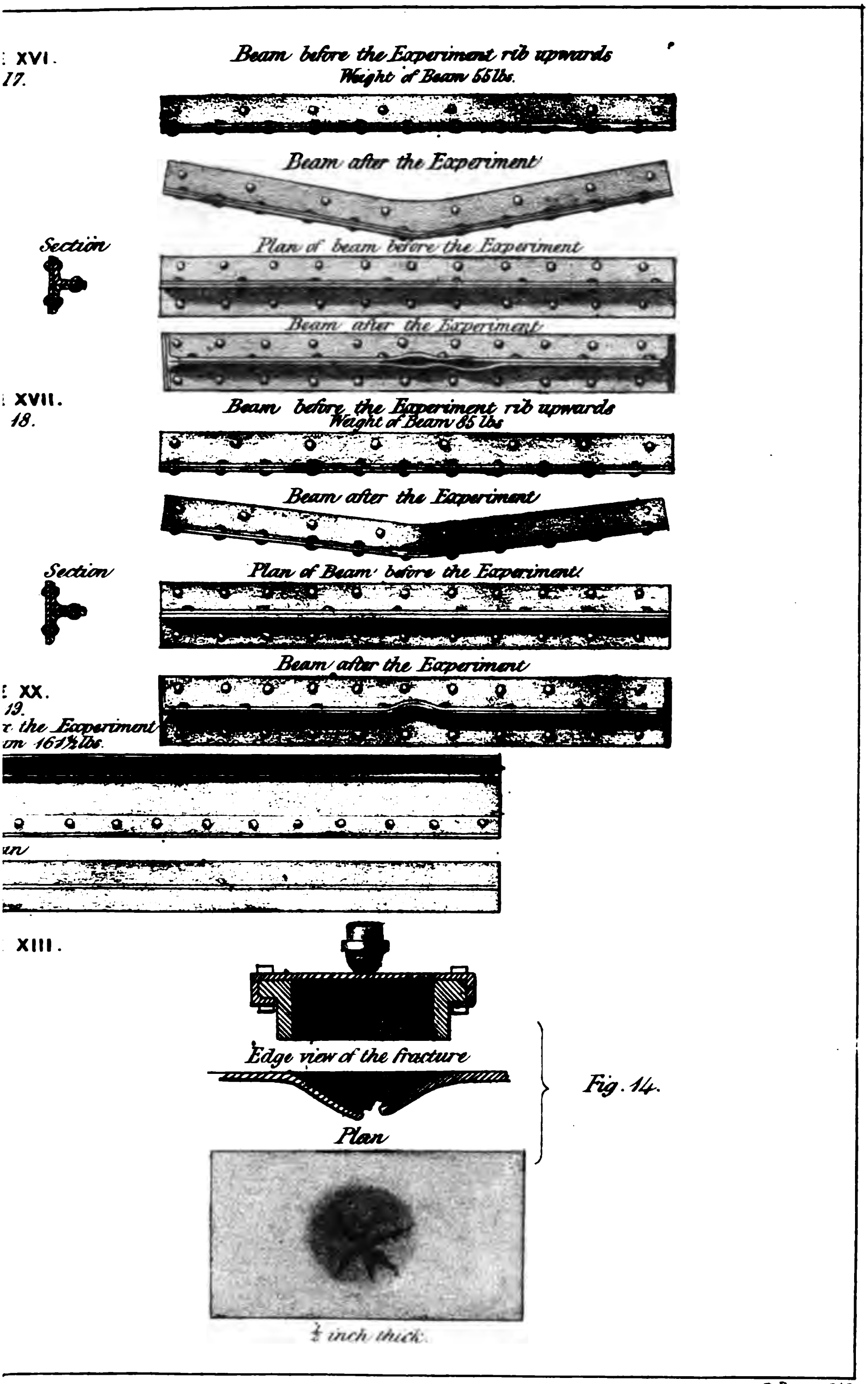


Edge view of the fracture

Plan

½ inch thick

TE V.



J Basire, Lith.